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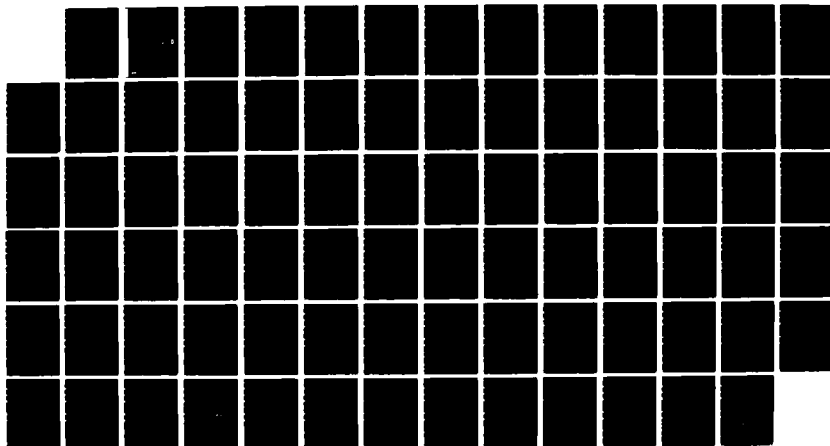
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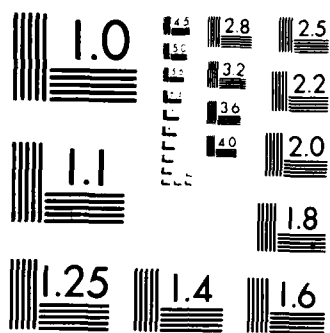
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DEVELOPMENT OF LIQUID METAL FIELD-EMISSION SOURCES FOR USE IN FAST REPETITIVE OPENING SWITCHES

January 1988

Final Technical Report
Covering the Period: 1 July 1986 through 31 October 1987

By: Michael J. Coggiola

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Prepared for:

OFFICE OF NAVAL RESEARCH
800 North Quincy Street
Arlington, VA 22217-5000

Attention: Dr. B. R. Junker, Director
Mathematical & Physical Sciences Directorate

Contract No. N00014-86-K-0596
SRI Project PYU-2448
MP 88-007

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SUMMARY

This final technical report covers all work performed by SRI International on Contract N00014-86-K-0596 for the period 1 July 1986 through 31 October 1987. The main objective of this research program was to establish the applicability of a novel, liquid metal field-emission electron source to the need for fast repetitive opening switches.

Liquid metal field-emission electron sources typically consist of a small capillary through which the liquid metal is forced. The application of a voltage between the capillary and an anode causes the liquid metal to form a sharp pointed cone. When the field at the cone tip exceeds the threshold for field emission, a large electron current flows to the anode. This electron pulse is accompanied by a rapid heating of the liquid, producing an explosive pressure rise. As the electric field is restored, the tip re-forms, resulting in a self-pulsing mode of operation. The pulse rate, average current, and current per pulse are all functions of the metal composition, emitter geometry, and diode voltage.

A number of the above-mentioned characteristics were studied during this contract period and are reported here. A single emitter tip was seen to produce current pulses in excess of 50 amperes, with a rise time of a few nanoseconds and a width of 5-50 ns. Pulsing rates vary between 10 Hz and 20 kHz under the conditions studied. Dispersed optical radiation was also measured and showed primarily emission from neutral atomic species presumably excited by electron impact in the gas phase. The results we obtained indicate that many of the operational parameters of these devices can be controlled, although the mechanisms are not yet understood. In particular, the enhanced mode of operation found for the Ga/In/Ar system gives very large, narrow current pulses by an unknown mechanism. The use of various diagnostics, including the dispersed optical emission, may provide some insight into these mechanisms.

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(To be published in Proceedings of SPIE Symposium on Innovative Science and Technology, Volume 871, 1988)	

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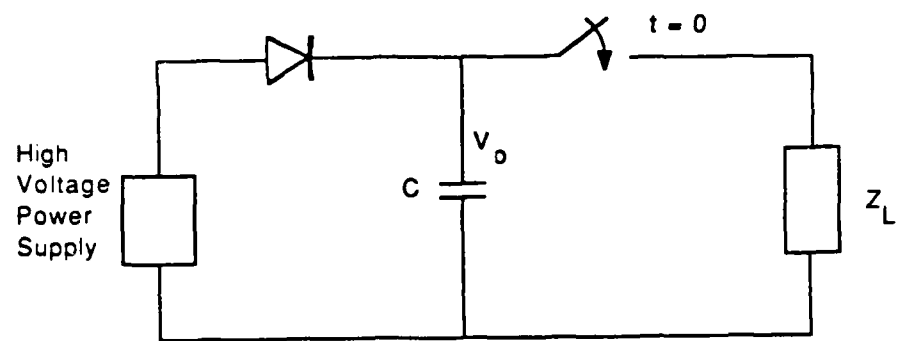
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INTRODUCTION AND BACKGROUND

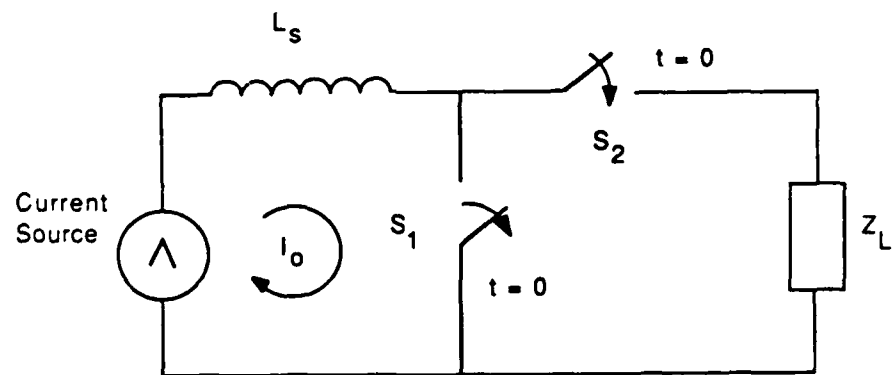
Many developing SDI and DoD technologies, such as directed energy applications, electromagnetic propulsion, and controlled fusion, involve the use of pulsed power technology. This technology normally involves capacitive storage of electrical energy that is rapidly delivered to a load by means of fast switches such as spark gaps, as shown in Figure 1(a). However, inductive storage is of considerable interest primarily because of the order of magnitude improvement in stored energy density. The key technological problem limiting the development of an inductive storage system is the lack of a fast, reliable, repetitive opening switch.

The basic circuit of an inductive storage system is shown in Figure 1(b). The major function of the opening switch is to conduct the current during the current buildup phase and then be capable of interrupting that current when it is desired to switch the current into the load. The opening process is a challenging assignment because of the large voltages that occur across the switch owing to $L \frac{di}{dt}$ emf as the current through the switch decreases. Because most applications involve the interruption of large currents (kilo- to mega-amperes) in short times (microseconds to nanoseconds), very large transient emfs can be expected; thus, any useful switch must be capable of complete electrical control under very strenuous conditions.

The feasibility of using inductive storage has been demonstrated using single-shot switches, but for most applications the need is for switches that can be operated repetitively and that promise reasonable lifetimes. Switches can be classified into two categories: true opening switches that maintain current control and uncontrolled current switches in which counterpulsing or other techniques are required to interrupt the current and force the switch to open. Vacuum triodes and electron-beam-controlled discharges fall in the first category, and vacuum arcs of various types belong in the second. The continuing research program described here focuses on a triode concept that falls in the true opening switch class. The active element of the triode is a



(a) Capacitive Energy Discharge Circuit



(b) Inductive Energy Discharge Circuit

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Figure 1.

liquid metal field-emission source. This novel electron emission source has a number of attractive features for the present application, including

- Low voltage control
- Fast response times
- High electron emission current density
- High voltage standoff
- Vacuum operation
- Constant restoration of emitter tips (self-healing).

Positive ion sources based on field evaporation/field ionization of liquid metals have been under investigation for a number of years. These sources have been successfully operated in a dc mode to produce ions of a wide variety of elements, including atomic and molecular ions of Li, Cs, Sn, Ga, In, Hg, Au, Bi, Ge, and U. In general, the liquid metal ion source (LMIS) consists of a solid metal nozzle or needle, typically made of tungsten, that is wet with a continuous supply of a liquid metal. When an electric field is established between the emitter tip and a suitable extraction electrode, the liquid metal is drawn into a sharp point such that the electrostatic and surface tension forces are balanced. The resulting cone tip is well described in the static case by the Taylor model;¹ however, in the actual fluid dynamic operation of the source, the tip behavior may be more complex.² Because of the very small radius of the cone tip (hundreds of Angstroms), the local electric field becomes sufficiently strong ($\sim 1 \text{ V/\AA}$) to extract positive ions from the liquid metal. Total emission currents in excess of 100 μA have been achieved in many cases, with very high long-term stability.

The conditions that exist at the tip of the LMIS described above can also produce electron field emission if the potentials are reversed. This type of source has been demonstrated by Swanson and Schwind.³ Although field-emission electron sources are well known and extensively used in electron microscopes, they have typically depended on solid needle-point "whiskers" of tungsten to produce the requisite field strength. On the other hand, the use of liquid metal sources for intense electron field emission has not been investigated in a systematic manner.

When operated in the electron field-emission mode, a Ga/In liquid metal emitter produced extremely high peak currents in a free-running self-pulsing mode.³ Current pulses with peak values of 40-60 A have been measured from a single tip, with rise times of 2 ns and 3-5 ns full width at half maximum (fwhm). The pulse repetition rate depends on the RC time constant of the circuit and the power supply. Repetition rates of between 40 and 80 kHz have been measured. In this mode, the current goes completely to zero after each pulse and stays at zero if the voltage is removed. The explanation offered for this pulsing behavior is that as the field is applied, the tip radius decreases, thus increasing the tip field strength and therefore the electron emission. Localized heating at the tip results from the energy-exchange processes that accompany field emission. This heating can be sufficiently rapid and extensive to evaporate the liquid metal in an explosive event that momentarily shorts the diode with a large burst of current. The tip then collapses because the field drops as the diode is shorted. However, as soon as the tip collapses and the current flow is interrupted, the field reappears, and the tip begins to re-form as the liquid metal flows into position to heal the damage. A new tip then begins to form, and the process repeats itself, leading to a rapid self-pulsing effect.

Two energy-exchange processes are responsible for the heating observed in the Ga/In source described above. At low electron emission currents, the energy exchange is dominated by the so-called Nottingham effect. This effect, which can produce either heating or cooling of the cathode, arises from the net difference in energy between the source of electrons (the liquid metal) and the free electrons emitted by the tip. The second energy-exchange process is the more familiar resistive, or Joule, heating. This latter process is important at higher emission currents and is due to the finite electrical resistance of the metal. Since large numbers of free electrons must be supplied from the electrical source through the liquid metal to the tip, the Joule heating produces a very rapid temperature rise.

A single liquid metal field-emission tip operating in the self-pulsing mode would not be applicable to the pulsed power situation under consideration here. However, the total peak current required for switching applications could be achieved by an array of such liquid emitters. If a 10 x 10 array of sources were made so that each of the 100 sources produced about 50-A peak

current pulses, then it would be possible to produce 5 kA of peak switched current. For such an array to work, all the tips would have to "explode" very nearly simultaneously because of the shorting effect of the tip explosion. This would require accurate fabrication of the cathode structure, or individually controlled tips all acting in parallel, or both. One feature of the liquid emitter seems to be that the onset of the explosive emission is repeatable for a given tip. Thus, it may be possible to make a small array with tips that can be individually biased to within a few volts of the onset of emission and then pulsed together to trigger simultaneous emission. The maximum current pulse reported by Swanson and Schwind for a single tip was 250 A. Thus, a four-tip array with simultaneous triggering would switch a 1-kA pulse.

Another alternative would be to fabricate a much larger array such that enough tips would explode at any given time to switch the required current loads. In a 100 x 100 array, only 0.04% of the tips would have to trigger simultaneously to switch the same load. If the average emission pulse is 10 ns and the self-pulsing rate is 100 kHz, then there is a high probability that four or more tips would trigger simultaneously. Thus, the multipoint array would not require individual tips to be controlled but rather would depend on the random pulsing of a large number of tips.

Another possible approach to the multitip array is the use of a linear source. Clampitt and coworkers⁴ reported that when molten metal forms a thin film along a linear structure ("razor blade") in the presence of strong electric field, a periodic cusp-like structure is generated. The periodicity of the cusps is determined by the field strength and the surface tension of the liquid. Each cusp then acts as a independent emission site, resulting in a one-dimensional, linear array of tips. Although Clampitt's work demonstrated this type of source only for ion emission, it is reasonable to expect a similar effect to produce electron emission under the correct conditions.

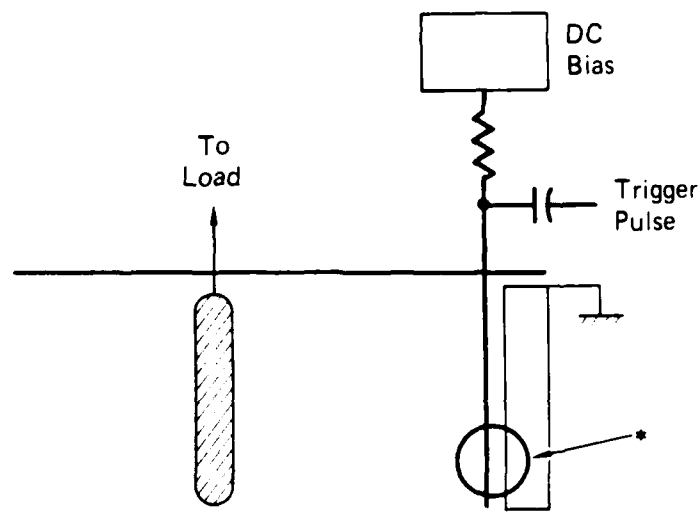
The liquid metal field emitter has several appealing features for the fast, repetitive switch application. It can deliver very large peak currents in a pulsed mode without destroying itself. It is self-healing in the event of discharge, since the working tip material is resupplied by the liquid. The liquid metal field emitter can supply its own positive ions for space charge neutralization. It can be shut off rapidly, and its emission is highly

repeatable for a given geometry. Figure 2 is a diagram of a triode-vacuum switch based on a liquid metal field-emitter array.

The nanosecond pulse lengths reported in the literature for liquid metal electron emission sources are too short with respect to the millisecond L/R time constants of the desired switching circuits. As noted above, liquid metal positive ion sources can easily operate in the dc mode. The explosive evaporation that Swanson and Schwind observed for the Ga/In electron source does not occur in the ion emission mode, primarily because the Nottingham effect serves to cool the source rather than heat it. Thus, if the electron source can similarly be made to operate in a mode in which the Nottingham effect does not heat the liquid metal tips during emission, long-pulse or even dc operation should be possible.

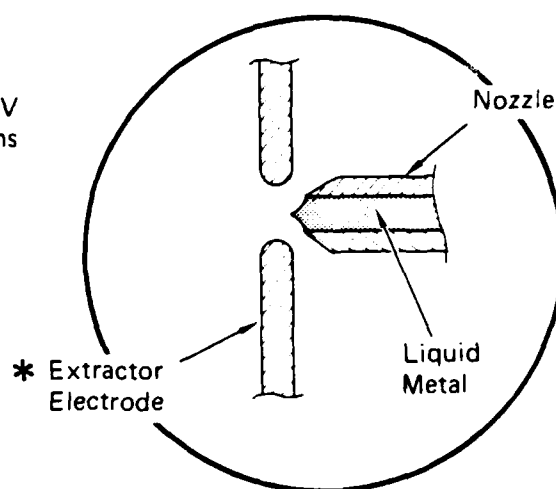
The factors that govern both the magnitude and sign of the Nottingham effect are complex functions of the liquid material properties (surface tension, work function, heat capacity, thermal conductivity, etc.), the field strength, the fluid dynamics of the system, and emission characteristics of the tips. Thus, it is not possible to determine beforehand which systems would yield electron emission with little or no energy transfer to the liquid metal tip. However, the systematic investigation of a variety of liquid materials in conjunction with differing tip geometries and substrate materials would provide much of the necessary information. For example, one attractive combination of emitter tip material and substrate material is liquid cesium flowing on a molybdenum needle tip. A partial monolayer coverage of cesium on molybdenum is known to produce a surface of very low work function (~ 1.1 eV). A number of other such combinations are known and may prove of value in this application. In fact, mixed emitter materials such as zirconium-oxygen-tungsten when used in a cold-cathode electron field-emission source have demonstrated significant cooling of the tips with increased emission.⁵

An additional possibility for controlling the emission characteristics of liquid metal tips is laser-assisted or -activated photoemission. Recent work on the electron emission characteristics of thin film alkali photocathodes indicates that large peak current density pulses (~ 75 A/cm²) can be readily obtained using low power laser excitation.⁶ This behavior suggests that the liquid metal tips could similarly yield large current density pulses of electrons under laser irradiation. This approach has the advantage of a very



Specifications:

$I \sim 10 \text{ kA}$
 $V \sim 10\text{-}30 \text{ kV}$
 Rise Time: ns



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Figure 2.

rapid switching time, governed by the laser pulse shape. Thus, an array of liquid emitters (either two-dimensional or linear cusps) could be biased to a point just below their nominal field-emission point and then switched on by a low-power, nanosecond laser pulse. If the tip bias voltage were simultaneously raised above the emission threshold value, then the electron emission initiated by the laser pulse might be sustained by the static field. This combination could produce long-pulse or even dc switch action with very fast switching time and high-peak-current density.

The use of laser initiated electron emission has been reported only with thin film alkali photocathodes and not with liquid metal tips sources of the type proposed for study. However, in preliminary experiments in our laboratory, we have observed that when a Cs^+ beam, formed using a single-tip liquid emitter, was irradiated with the unfocused 514.5-nm line from an Ar^+ laser, positive ion emission stopped. At the same time, intense electron emission was detected. A systematic study of this process using the wide variety of laser excitation sources available, with regard to both pulse characteristics and photon energy, is needed to apply this triggering method.

RESEARCH PROGRESS

The goal of the initial phase of research was to investigate the pulsing characteristics of a simple single-tip liquid metal field-emission source. Because this type of source has only been described briefly in the literature by Swanson and Schwind,³ it was important to duplicate their results. Experimentally, this task consisted of assembling a suitable vacuum test stand, fabricating a liquid metal field-emission diode, and measuring its electron emission characteristics. Each of these tasks is described below, along with a presentation of some representative results. Additional details and discussion can be found in the Appendix, "Characteristics of a Pulsed, Liquid Metal Field-Emission Source for Use in Fast High-Current Switches," presented at the Symposium on Innovative Science and Technology, Los Angeles, CA, in January 1988.

Experimental Details

The vacuum test stand used for this work consisted of a large (45-cm diameter, 25-L volume) aluminum chamber pumped by a baffled 6-in. oil diffusion pump. Base pressures were typically 1×10^{-6} Torr, rising to varying degrees (see below) when the source was operating. The front flange of the chamber was fabricated from Lucite to allow continuous observation of the emitter tips under actual operating conditions. In addition, a smaller window was provided on the rear vacuum flange to permit observation of the optical emission spectrum accompanying the electron emission.

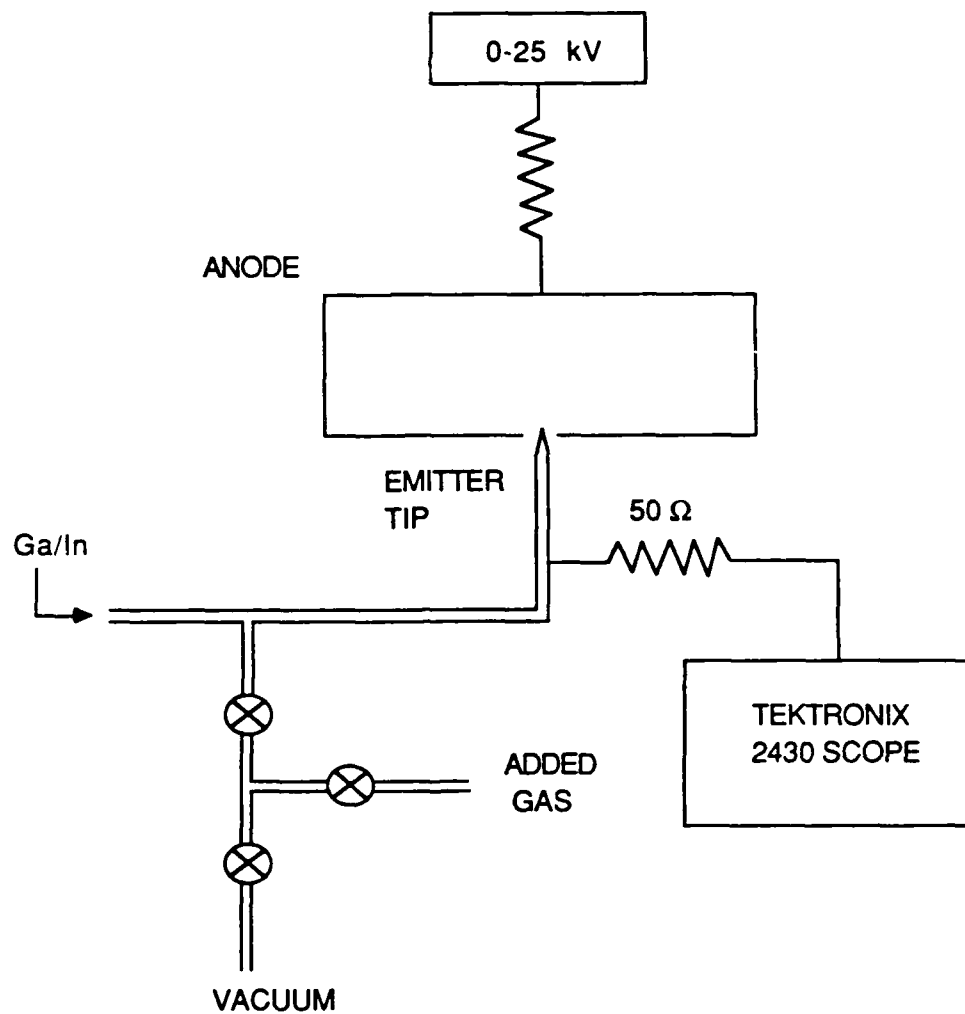
We investigated three liquid metal field emitter tip configurations, including a commercially available tungsten needle.⁷ This needle has a nominal opening of 0.001 in. In the simplest configuration, the needle is mounted to a Swage-lock fitting connected to a length of 0.25 -in. diameter Teflon tubing. The tubing exits through the vacuum chamber and serves as the feed source for the liquid metal and permits adjustment of the pressure behind the emitter tip. Figure 3 is a diagram of the standard emitter tip experimental configuration. The Teflon feed line can be evacuated or pressurized with an added gas.

The other two emitter tip geometries consist of an open pool of liquid metal with an etched tungsten whisker protruding through the droplet or a heated pool of liquid metal without the whisker. These configurations are illustrated in Figures 2(a) through (c) of the Appendix.

The emitter tip forms the cathode of a simple diode structure. The anode is formed by an extraction aperture and collector plate that are spaced apart by 10 cm but electrically connected. The tip is mounted such that it is coplanar with the 0.25-in.-diameter extraction aperture. This configuration essentially duplicates that of Swanson and Schwind. Electrically, the anode structure is connected to a variable 0- to 25-kV power supply through either a 10-M Ω or 100-M Ω ballast resistor. The cathode tip is grounded through the 50- Ω input impedance of a Tektronix model 2430 digital storage oscilloscope.

Operation of the liquid metal field-emission source is straightforward. Before the test stand is evacuated, a supply of Ga/In alloy (a liquid at room temperature) is placed in the Teflon tube near the emitter tip. During pump-down of the test stand, the volume behind the Ga/In supply is evacuated using the pumping system shown in Figure 3. This step prevents the trapped gas behind the liquid metal from forcing the alloy through the tip into the low pressure region of the main chamber. Once the test stand has been evacuated, the liquid metal must be pressurized, so that begins to flow through, and wet, the tip. Once liquid metal is seen to protrude from the tip, the high-voltage bias can be applied. The open pool emitter configurations require no special preparations for operation. The liquid metals will typically wet the tungsten whisker and be pulled along its length to the tip. The heated emitter begins operating as soon as the temperature is raised to the melting point of the metal.

Depending on the exact tip configuration, prior conditioning, etc., the voltage threshold for field emission may vary from a few to 15 kV. At threshold, the electron emission is somewhat erratic, triggering the scope at random. However, with only a modest increase in voltage above threshold (1-200 volts), the emission becomes more stable. Using the averaging capability of the 2430 scope, we can accumulate a number of electron pulses to accurately measure the average pulse height and time behavior.



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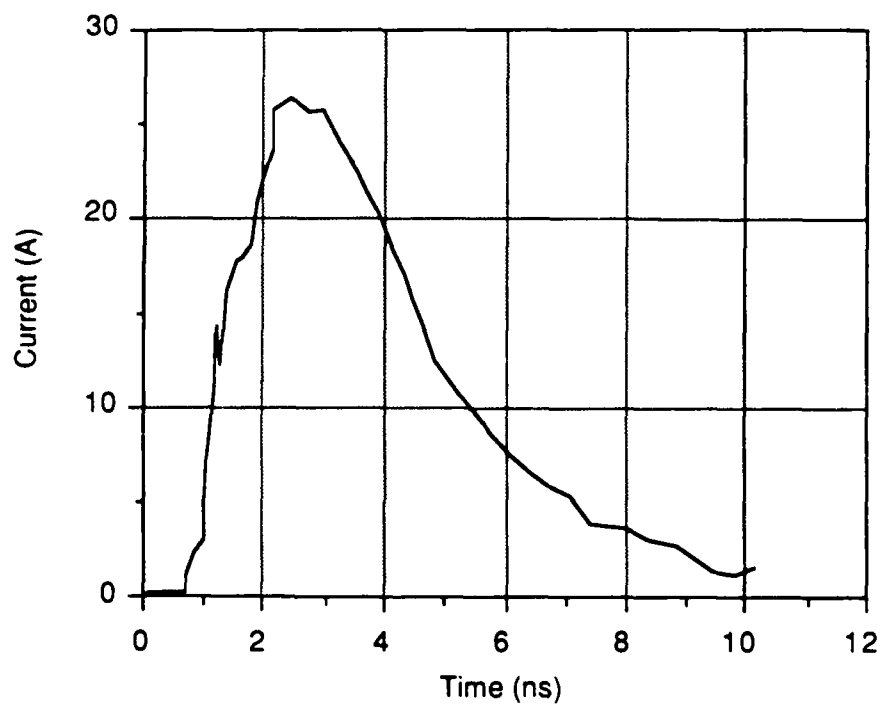
Figure 3. Experimental configuration used to measure pulsed electron field-emission characteristics.

Pulsed Electron Emission Characteristics

Figure 4 shows a typical trace recorded in the manner described above. The average peak pulsed electron current is seen to be ~26 amperes. The pulse rise time is measured to be 1.6 ns, with an fwhm of 3.5 ns. Under our experimental conditions (effective circuit capacitance of 30 pF), the measured repetition rate was 10-20 kHz. Although this pulsing rate is somewhat slower than that reported by Swanson and Schwind (40-80 kHz), the pulse shape and peak current are comparable. This simple emitter configuration yielded stable operation for many hours with a signal of the type characterized by the trace in Figure 4. To sustain this long-term operation, however, we had to apply a slight positive gas pressure behind the liquid metal. Even under these conditions, the pressure rise in the chamber amounted to only 5×10^{-5} Torr. This small pressure rise indicates that the gas used to force the Ga/In alloy through the tip does not pass directly into the vacuum chamber.

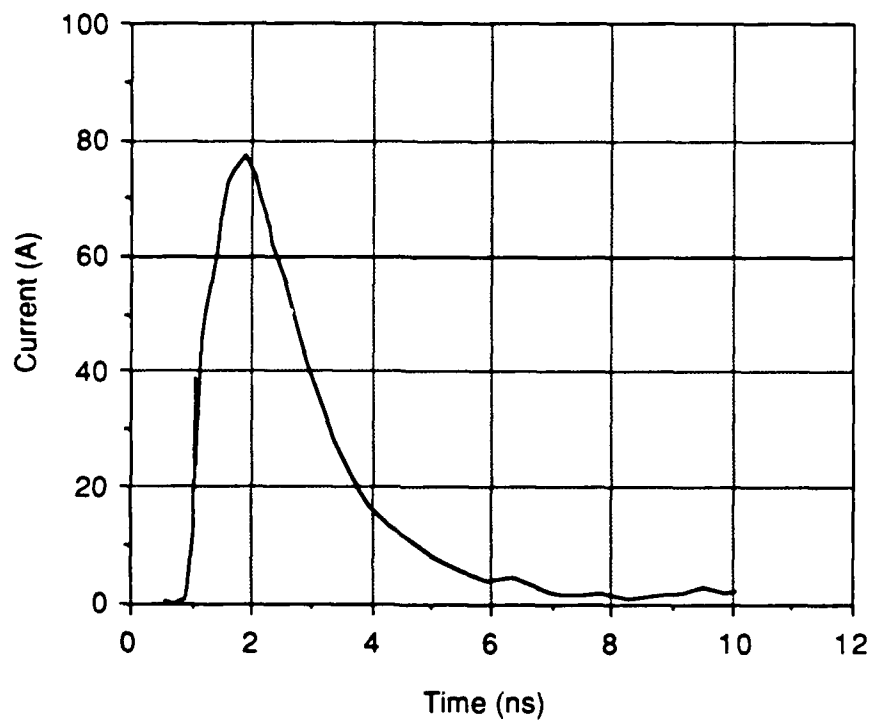
An alternative operational mode was observed when the added gas pressure was increased beyond that required to sustain a normal liquid metal tip. This alternative mode was characterized by a greater rise in chamber pressure ($5-8 \times 10^{-4}$ Torr), indicating that the added gas was "channeling" through the liquid metal and passing directly into the vacuum chamber. A typical electron pulse in this mode is shown in Figure 5 using argon gas with the same Ga/In alloy that produced the results in Figure 4. The peak electron current clearly is greatly enhanced, reaching ~78 A. In addition, the rise time is now less than 1 ns, while the fwhm is also reduced to 1.4 ns.

The mechanism responsible for this improved performance is not yet understood. However, prolonged operation in this mode (many hours) results in a significant erosion of the emitter tip. This erosion typically resulted in an increase in throat size from 0.001 in. to as much as 0.010 in. Some additional qualitative observations can be made concerning operation in the enhanced mode relative to the normal mode. In the normal mode, electron emission is accompanied by optical radiation produced at the tip. This optical emission was also observed by Swanson and Schwind to be localized at the tip [compare Figure 4(c) in reference 3]. Visually, this emission appeared to be bluish-white, with a very small spacial extent. On the other hand, in the added gas mode with argon, the appearance of the optical emission changed significantly. Under this mode, the spacial extent of the emission was much



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Figure 4. Field-emission electron pulse for Ga/In (75/25) with anode at 10 kV.



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Figure 5. Field-emission electron pulse for Ga/In (75/25) with added argon gas at 10 kV anode voltage.

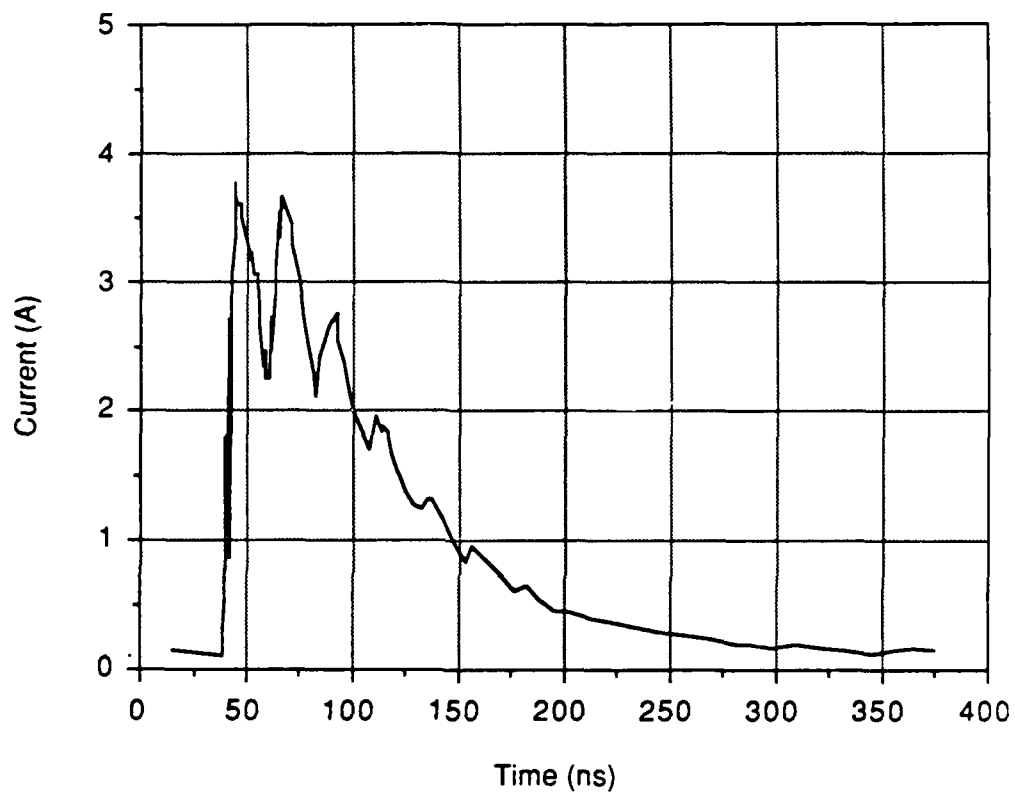
larger (many millimeters) and had an appearance more characteristic of an argon emission spectrum. These qualitative observations were substantiated by measurements of the dispersed emission spectra (see below). In addition to the changes in the light emitted from the tip region under the two operating modes, the added gas mode also produced an incandescent region just at the rim of the emitter. Because of the small size of the tip, this region cannot be localized to the inside of the tip, the rim itself, or the entire tip region. The incandescence seems to indicate that the tip region is being bombarded, most likely by positive ions accelerated in the extraction field. In addition to causing the incandescent glow, these ions may also generate secondary electrons that would contribute to the enhanced field-emission pulse. This mechanism does not, however, address the changes in the temporal behavior of the electron emission. In fact, a simple calculation shows that for the experimental extraction field strength of $\sim 3.2 \times 10^4$ V/cm (10 kV between the tip and the extraction electrode, 0.32-cm spacing), argon ions could only reach the tip in a time short compared with the 1-ns rise time of Figure 5 if they were formed within 4×10^{-4} cm of the tip region. However, ions formed that close to the tip would only be accelerated to 12 eV before striking the emitter. This energy is not sufficient to produce secondary electrons. Moreover, the primary electrons emitted by the tip would similarly have only about 12 eV of energy at the 4×10^{-4} cm distance, where argon ions would need to be formed by electron impact ionization. Since this energy is below the argon ionization potential, this mechanism does not seem to fit the observations. Nonetheless, some interaction between the added gas and the tip causes the incandescence, although it is not clear at this time whether this process is related to the enhanced electron emission or altered pulse shape.

We conducted several brief experiments using added gases other than argon. Both helium and hydrogen produced similar results: enhanced electron emission with a corresponding narrowing of the pulse length. Because the exact conditions are difficult to reproduce using the existing configuration, we cannot determine if the gas pressure and liquid metal supply were comparable from one gas species to the next. Thus, we cannot determine from these results if one of these gases is more effective than another at enhancing the electron emission. This type of quantitative comparison requires a configuration that uses an independent liquid metal feed system so that the emitting tip can be maintained constant while only the added gas species is changed.

We also tested an alternative method of adding argon gas to the system. Rather than adding the gas to the liquid metal feed system, we simply admitted the gas to the vacuum chamber to give the same approximate pressure rise. The enhanced mode of operation could not be produced under those condition, but rather the emitter behaved exactly as with only the Ga/In. Thus, it appears important for the argon to be at a relatively high pressure at the local site of electron emission.

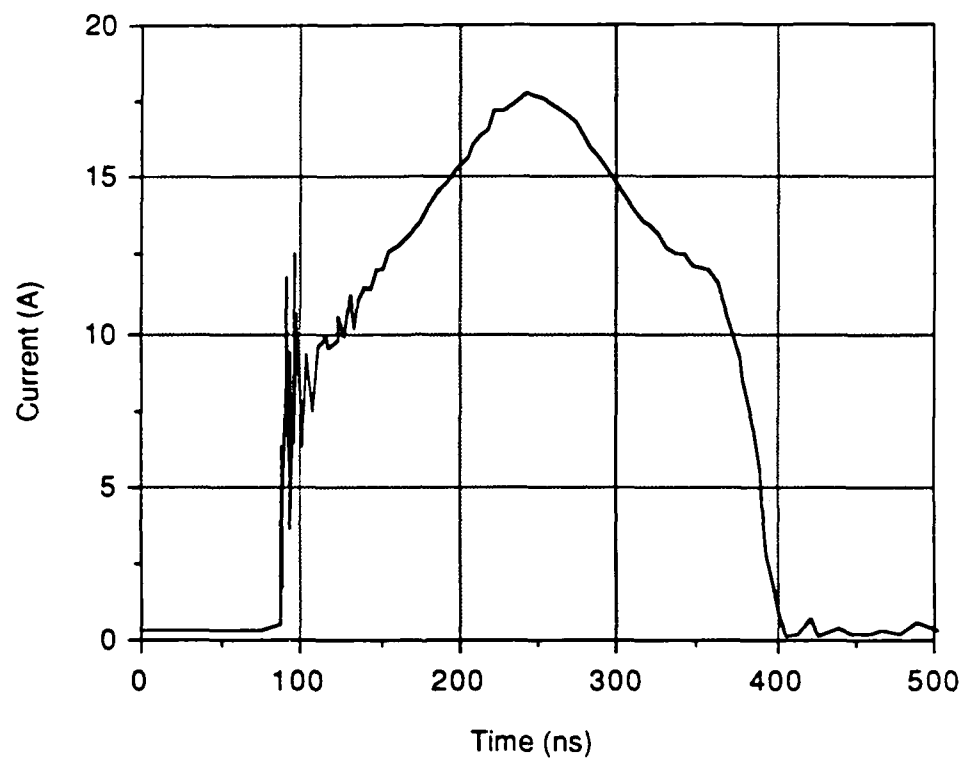
While experimenting with the added gas operational mode, we observed that very high flow rates of argon (as determined by a correspondingly large rise in chamber pressure) produced a pulsed electron field-emission signal with a much longer pulse length. We conducted further experiments using the configuration in Figure 3 without liquid metal. A typical electron pulse is shown in Figure 6 for argon at 10-kV anode potential. Although the peak current is only 3-4 amperes, the fwhm is >50 ns while the rise time remains below a few nanoseconds. The rapid oscillatory structure may be due to signal-processing effects, although it is somewhat reproducible. Interestingly, the electron field-emission using only argon gas is also pulsed at a rate of a 1-2 kHz. Clearly, the origin of the pulsing with pure argon is not the same as for the collapse/reformation mechanism of the liquid metal. The pulsing is most likely due to the complete shorting of the diode caused by the large integrated current flow followed by collapse of the electric field. Although the field is reestablished rapidly, the limited capacity of the power supply, coupled with the circuit capacitance (30 pF), leads to a "charging" time of ~ 1 ms before electron emission can be initiated again.

By increasing the capacitance of the charging circuit from 30 pF to 500 pF using an external capacitor, the pulsed electron signal shown in Figure 7 was obtained. Under these conditions, the peak current is 18 A, with a fwhm of ~ 300 ns. The field emission signal appears to have the same initial rise time and structure as the low capacitance pulse in Figure 6. However, after a few tens of nanoseconds, the current begins to increase again, then peaks, and falls to zero. This unusual temporal behavior is not fully understood. In this mode, the repetition rate fell to ~ 100 Hz, probably owing to the limitations of the power supply. The corresponding average pulsed current in this configuration is 0.36 mA, or 3.6 kW, of average power from a single emitter tip.



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Figure 6. Pulsed electron field-emission using only argon gas.
Effective circuit capacitance of 30 pF. Anode voltage 10 kV.



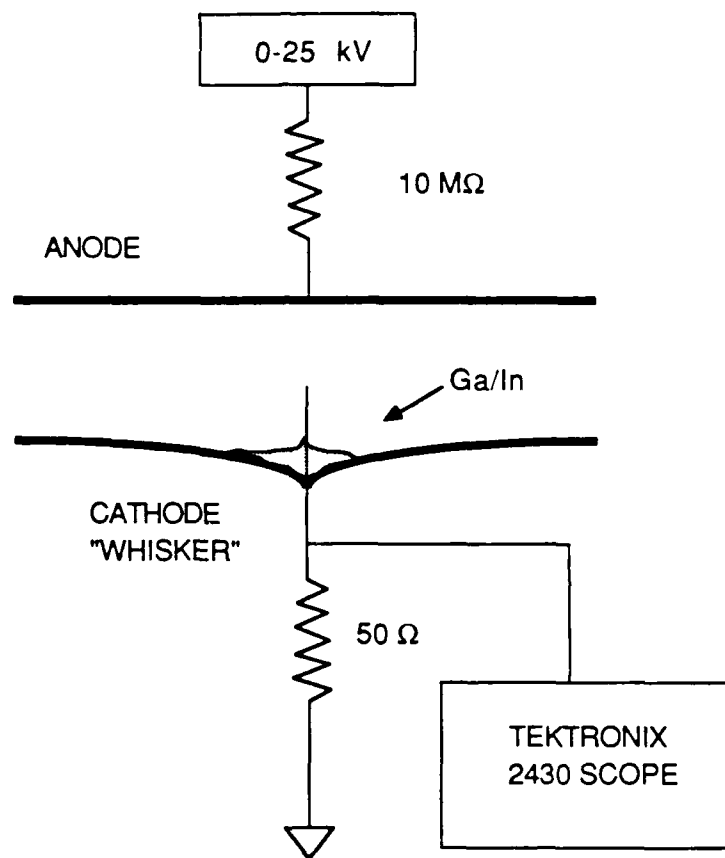
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Figure 7. Pulsed field-emission signal using only argon gas.
Effective circuit capacitance of 500 pF. Anode voltage 10 kV.

However, as did the Ga/In/Ar mode, the gas-only mode resulted in a significant erosion of the emitter tip within a few hours of operation. Similar field emission mechanisms may be responsible for the increased electron current observed in the presence of gas. Simply reversing the power supply polarity produced a very stable, dc discharge ion source. This mode of positive ion formation is typical of both hollow cathode sources and the commercially produced "Capillatron" ion source.

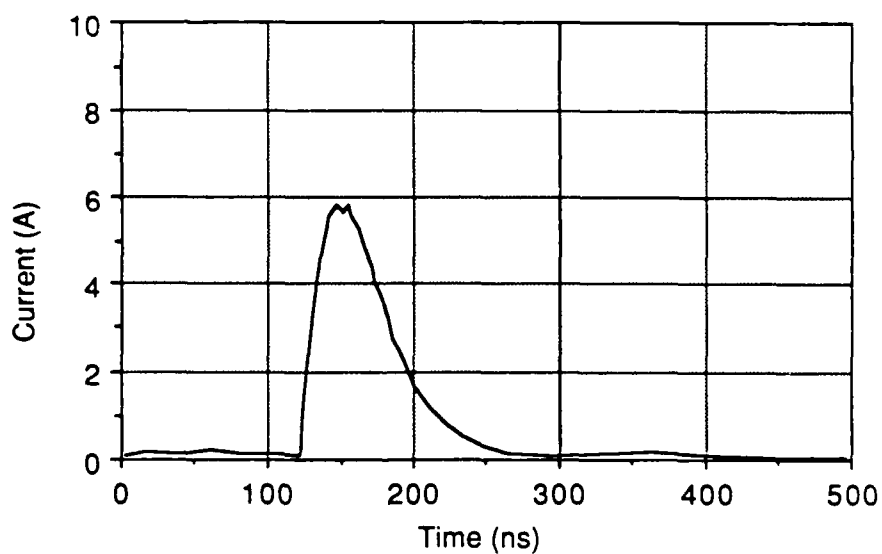
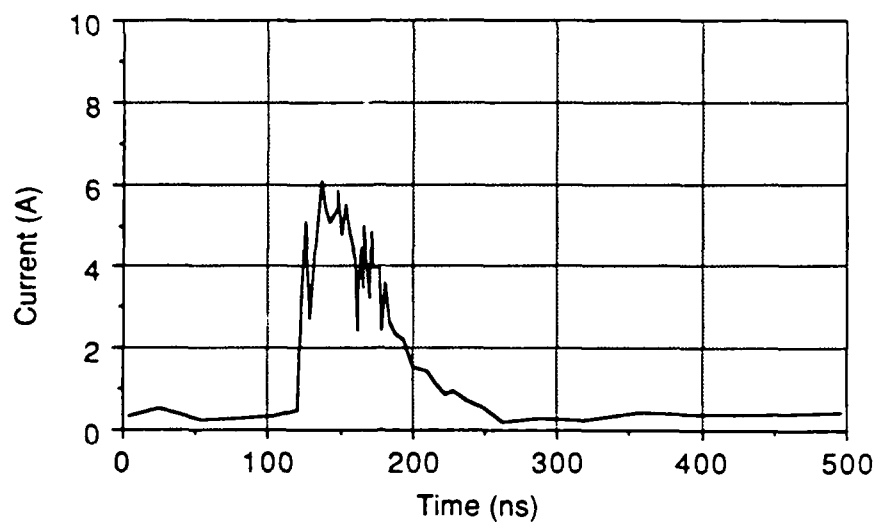
Two major shortcomings of the simple needle-type emitter tips are the difficulty sometimes encountered in wetting the tip and producing a continuous flow of metal and the erosion noted in enhanced mode operation. To overcome these problems, we tested an alternative field emission device, as shown schematically in Figure 8. The emitter tip consisted of a 0.001-in. diameter tungsten wire etched to produce a very fine whisker tip. The liquid metal was then "pooled" around the tip in a small depression formed in the cathode plate. We used a ternary eutectic of Ga/In/Sn (62.5/21.5/16) having a melting point of 10.7°C. This configuration operated reliably, producing modest peak currents and pulse shapes typified by the oscilloscope traces shown in Figure 9. The peak current in Figure 9 is 6 A, measured both as the electron pulse arriving at the anode and as the current drawn by the cathode. The measured rise time was generally long, 30-50 ns, with a fwhm of 50-75 ns. This type of field-emission source has the advantage of simplicity over the needle-type source, at the expense of lower currents. A possible reason for the reduced peak current levels is the limited supply of metal available at the tip of the tungsten whisker.

The threshold for electron emission depends primarily on the electric field at the tip of the liquid metal. The tip radius, in turn, depends on the liquid metal used. To a first approximation, the radius is proportional to $\gamma_s^{1/2}$, where γ_s is the surface tension of the liquid. Figure 10 shows the average field emission currents measured as a function of diode voltage for indium ($\gamma_s = 560$ dyn/cm), gallium/indium ($\gamma_s = 690$ dyn/cm), and potassium ($\gamma_s = 86$ dyn/cm). The measured thresholds for indium and gallium/indium are similar, whereas that for potassium is much lower. This trend is in qualitative agreement with the expected dependence on surface tension. In addition, the results in Figure 10 show that the average current is a linear function of the applied voltage over the range studied. Furthermore, the average current



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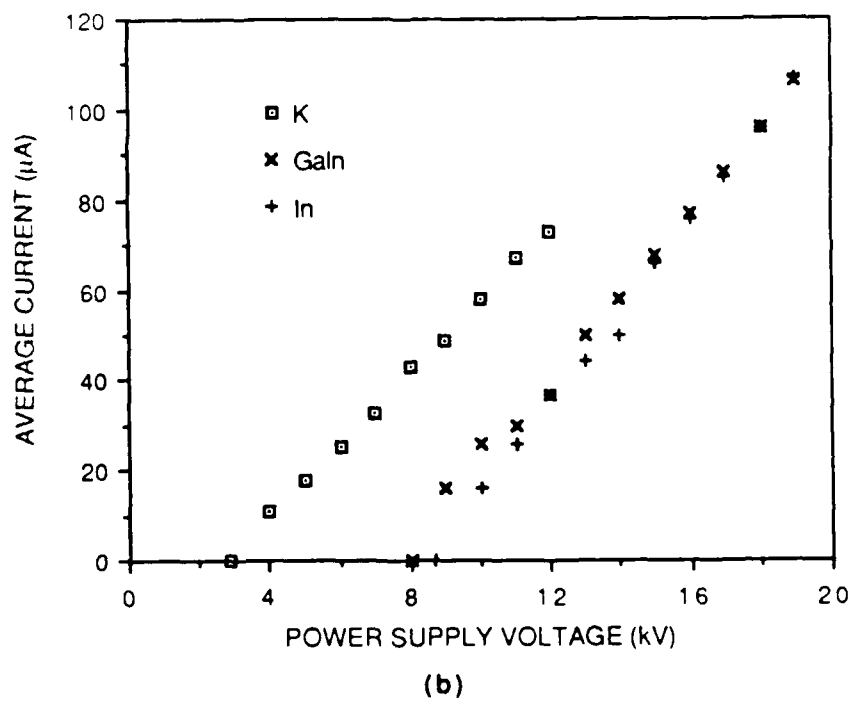
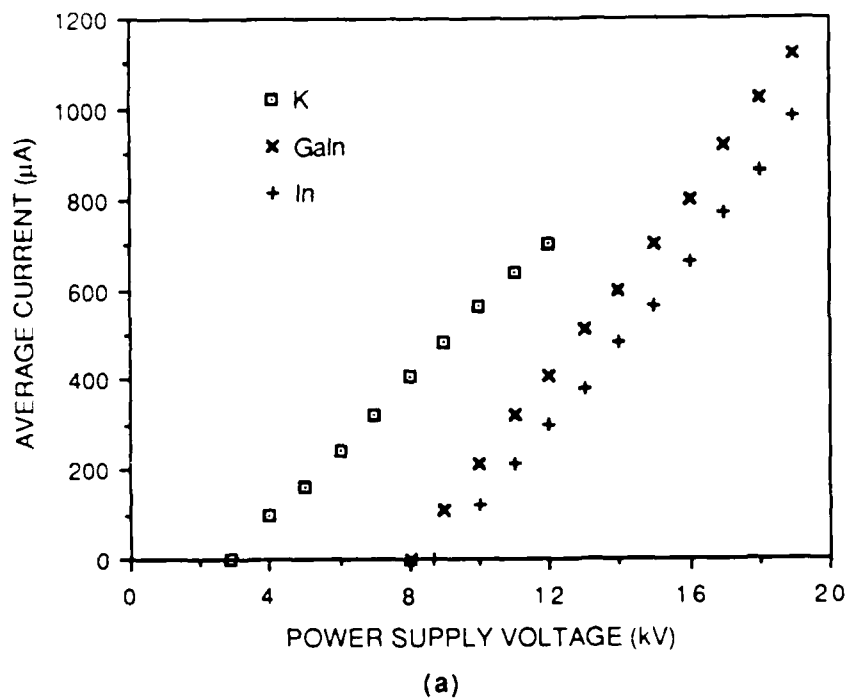
Figure 8. Alternative liquid metal field-emission configuration using a wetted whisker.



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Figure 9. Electron field-emission pulse from Ga/In/Sn using configuration shown in Figure 8.

The anode signal (at 12 kV) is shown in the upper trace. Lower trace is the cathode pulse.



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Figure 10. Average electron emission current as a function of the power supply voltage.

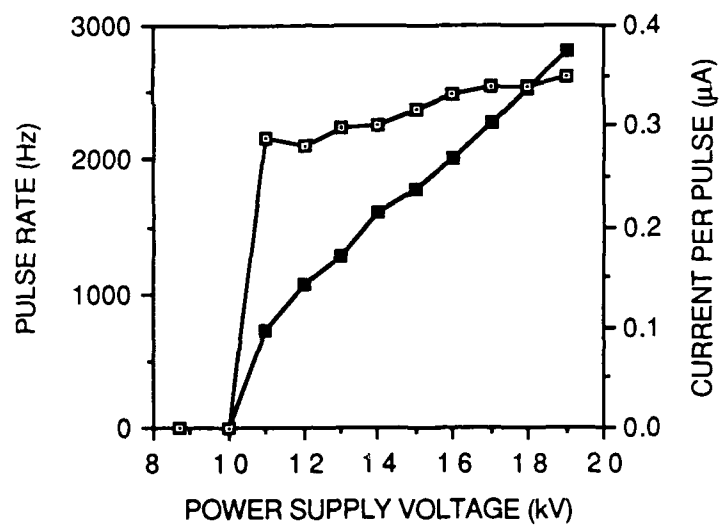
Ballast resistor: (a) 10 M Ω ; (b) 100 M Ω .

measured with a 10-M Ω ballast resistor is approximately a factor of 10 larger than the corresponding values measured with a 100-M Ω resistor. This scaling with load resistance indicates that the current/voltage behavior of the diode is determined by the ability of the power supply to charge the circuit to the required voltage following each electron pulse.

Figures 11 and 12 show the measured pulse repetition rate for an indium emitter as a function of applied voltage with the 10-M Ω and 100-M Ω ballast resistors, respectively. As expected, the pulse rate is a linear function of the diode voltage. Since both the average current (Figure 10) and pulse rate (Figures 11 and 12) are linear functions of the voltage, the current per pulse remains essentially constant with voltage, as clearly shown by the data in Figures 11 and 12. Apparently, once the diode exceeds the threshold voltage, the electron pulse size cannot be increased by increasing the voltage. This behavior implies that the maximum possible surface area is active for voltages just above threshold. The only effect of raising the diode voltage is to reduce the charging time between pulses.

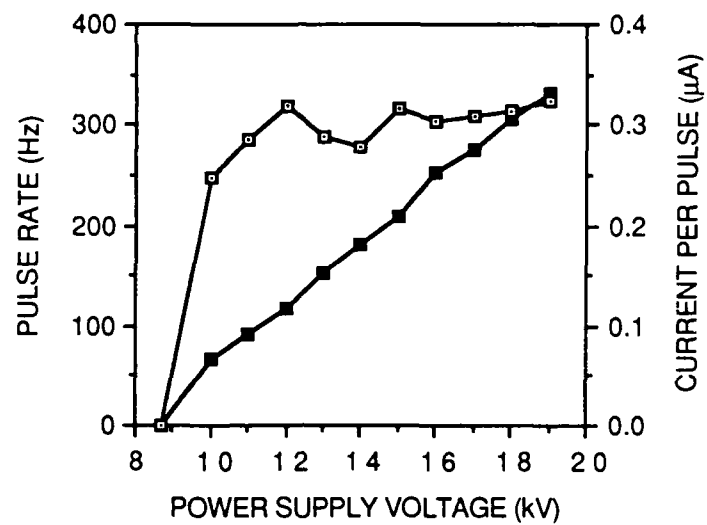
Figures 13 through 16 give the corresponding results measured for gallium/indium and gallium/indium/tin. In each case, not only is the current per pulse constant above threshold, but its absolute value is very similar, ranging between 0.3 and 0.35 μ A. In contrast, Figures 17 and 18 show the results for potassium, where the current per pulse is seen to be much smaller, 0.052 μ A, although it is still constant with voltage. This marked difference may be associated with the differing work functions and thermal conductivities of the metals.

Swanson and Schwind³ reported that prior to the onset of explosive emission, an ~ 3 -ns period of slow current rise could be seen, corresponding to pure electron field emission. A similar result is found here, as shown in Figure 19. In the present case, the linear onset period appears to be ~ 10 ns and reaches an amplitude of only a few milliamperes before the main pulse is produced. On the other hand, Swanson and Schwind found the onset of explosive emission to occur at ~ 50 -mA emission. These differences may be associated with the different liquid metals used and the different diode geometries.



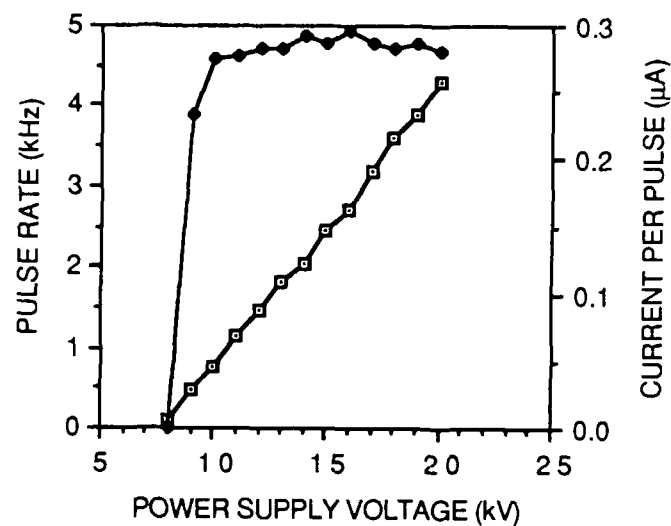
RA-M-2448-19

Figure 11. Pulse rate (■) and current per pulse (□) for indium liquid metal emitter as a function of applied diode voltage with a 10 M Ω load.



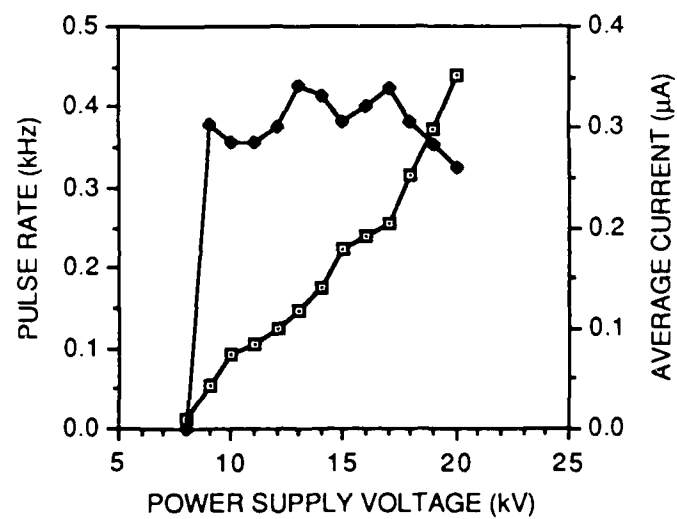
RA-M-2448-20

Figure 12. Pulse rate (■) and current per pulse (□) for indium liquid metal emitter as a function of applied diode voltage with a 100 MΩ load.



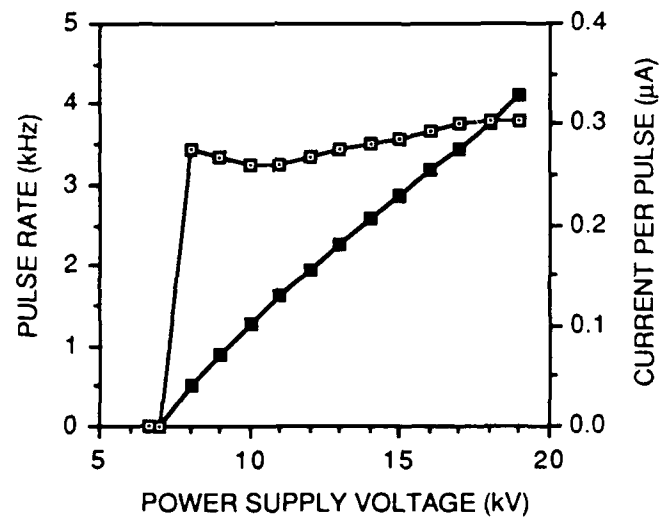
RA-M-2448-21

Figure 13. Pulse rate (□) and current per pulse (◆) for gallium Indium liquid metal emitter as a function of applied diode voltage with a 10 MΩ load.



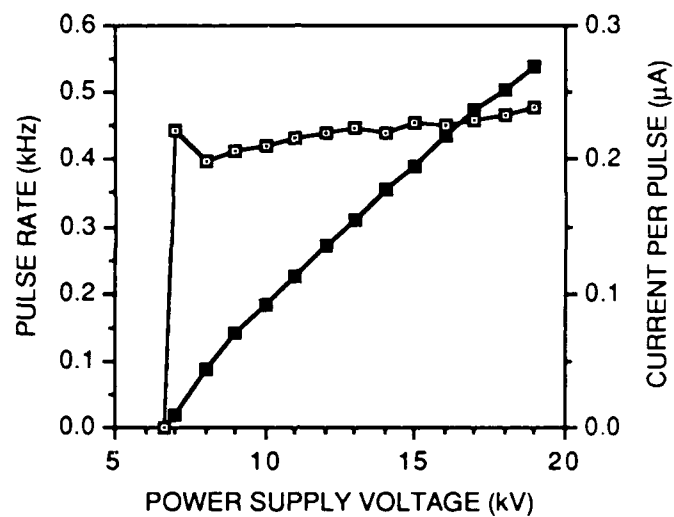
RA-M-2448-22

Figure 14. Pulse rate (□) and current per pulse (◆) for gallium indium liquid metal emitter as a function of applied diode voltage with a 100 MΩ load.



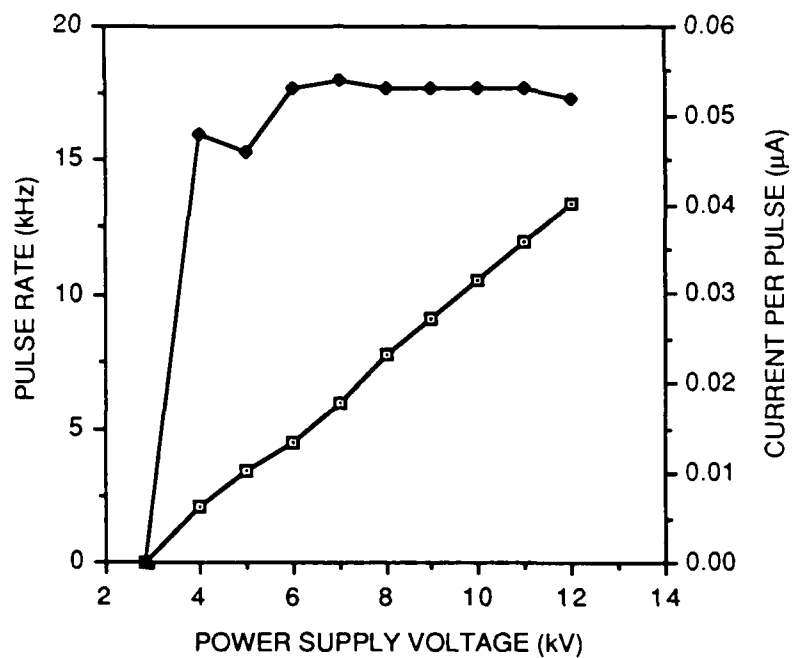
RA-M-2448-23

Figure 15. Pulse rate (■) and current per pulse (□) for gallium indium tin liquid metal emitter as a function of applied diode voltage with a 10 MΩ load.



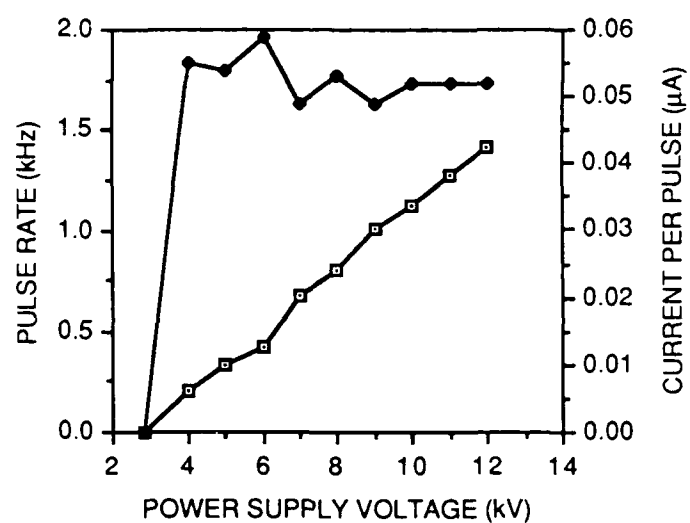
RA-M-2448-24

Figure 16. Pulse rate (■) and current per pulse (□) for gallium indium tin liquid metal emitter as a function of applied diode voltage with a 100 MΩ load.



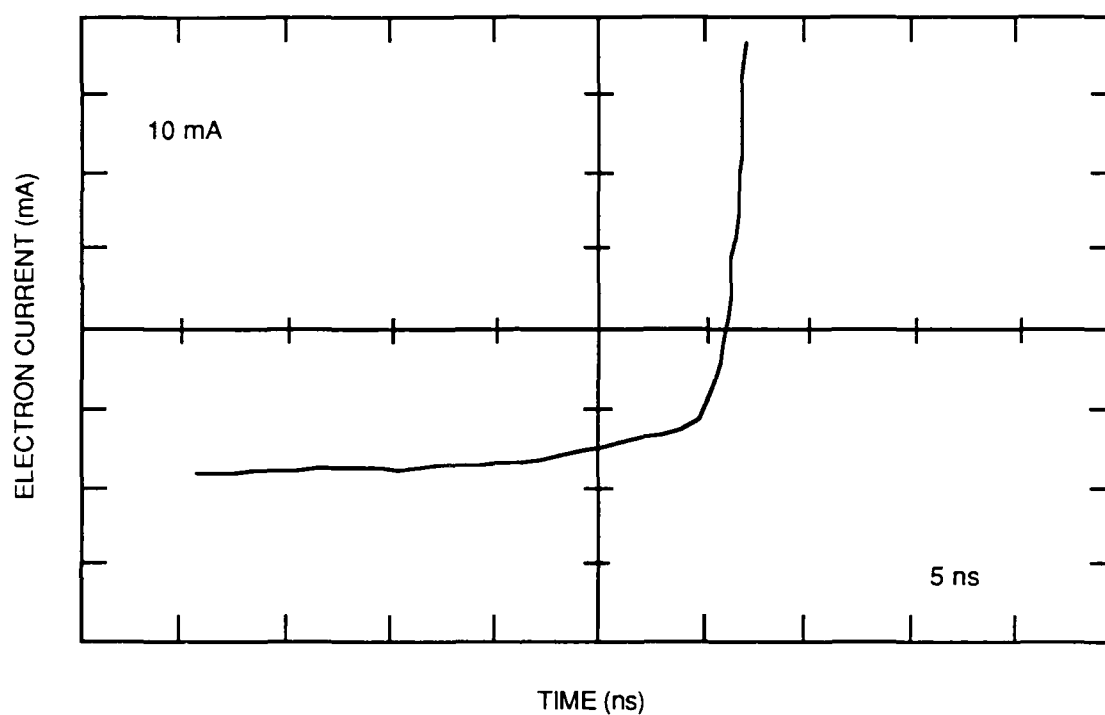
RA-M-2448-25

Figure 17. Pulse rate (□) and current per pulse (◆) for potassium liquid metal emitter as a function of applied diode voltage with a 10 M Ω load.



RA-M-2448-26

Figure 18. Pulse rate (□) and current per pulse (◆) for potassium liquid metal emitter as a function of applied diode voltage with a 100 MΩ load.



RA-M-2448-27

Figure 19. Threshold electron emission for gallium indium tin liquid metal emitter at 15 kV.

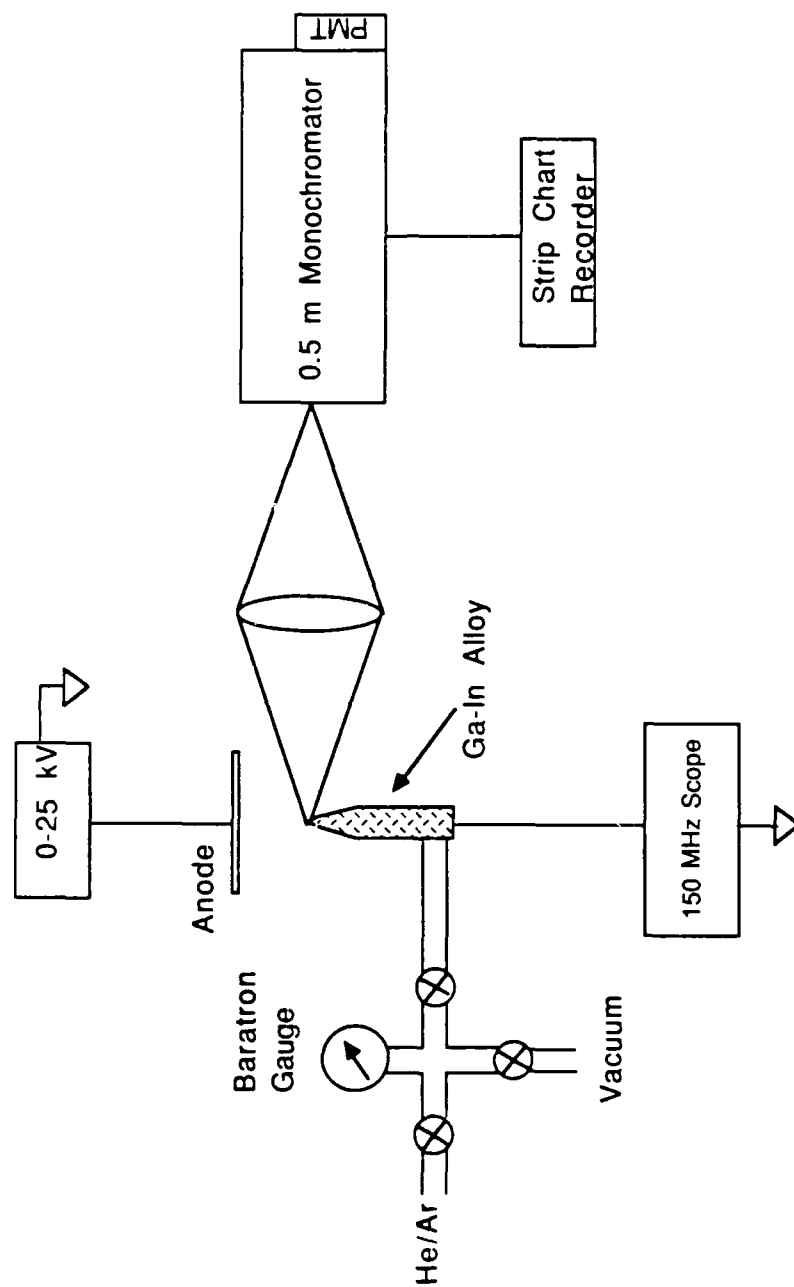
Optical Emission Studies

Under normal operating conditions, the liquid metal field emission electron source produces a considerable level of optical radiation. As noted above, the spacial extent and qualitative appearance of the optical emission changes with the mode. With only the Ga/In alloy, the emission appears at the very tip of the needle and is bluish-white. This emission was also observed and photographed by Swanson and Schwind.³ In the enhanced mode with argon as the added gas, the optical emission is more diffuse, extending many millimeters from the tip, and has an appearance more characteristic of argon discharge. Although this optical emission was observed previously, the dispersed spectrum apparently was not measured. It seems reasonable to assume that the spectrum contains information on the emitting species and may shed some light on the mechanisms producing the electron emission in each mode.

The experimental arrangement shown in Figure 20 was assembled to record the optical emission spectrum produced by the liquid metal field-emission source. The light from the emitter tip was focused onto the entrance slit of a scanning 0.5-m monochromator equipped with an RCA 8850 photomultiplier tube. Optical spectra were recorded using a PDP 11/2 computer to slowly scan the monochromator while counting the pulses from the photo tube. The overall light collection efficiency was not very high, and wide monochromator slits were needed to obtain measurable signal levels. The resulting spectral resolution was typically 0.5-1 nm. This resolution is sufficient to identify some of the observed emission lines, particularly those associated with argon; however, it is too low to assist with identification of many unassigned lines (see below). Furthermore, because of the low signal levels, long scan times were required (20-60 minutes), during which it was difficult to maintain the steady operation of the source. Thus, relative peak heights cannot provide reliable information.

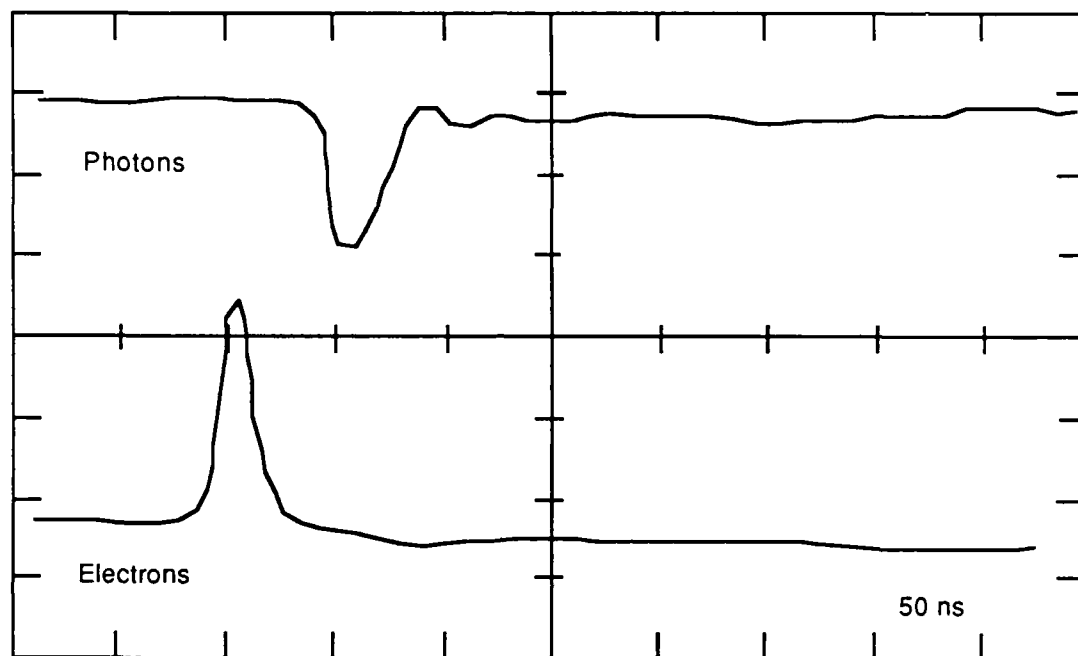
Since we can assume that the optical emission is directly associated with the electron pulse, it should be temporally correlated. Figure 21 shows the oscilloscope traces corresponding to the electron pulse (lower trace) and the photon pulse (upper trace). The apparent 50-ns delay is accounted for by the photoelectron transit time of the 8850 photomultiplier tube.

Figure 22 shows a typical optical emission spectrum between 400 and 500 nm with the source operating with Ga/In only. The conditions were similar



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Figure 20. Experimental configuration used to measure optical emission from liquid metal emitter tips.



RA-M-2448-28

Figure 21. Electron and photon emission signals for an indium emitter at an applied diode voltage of 10 kV.

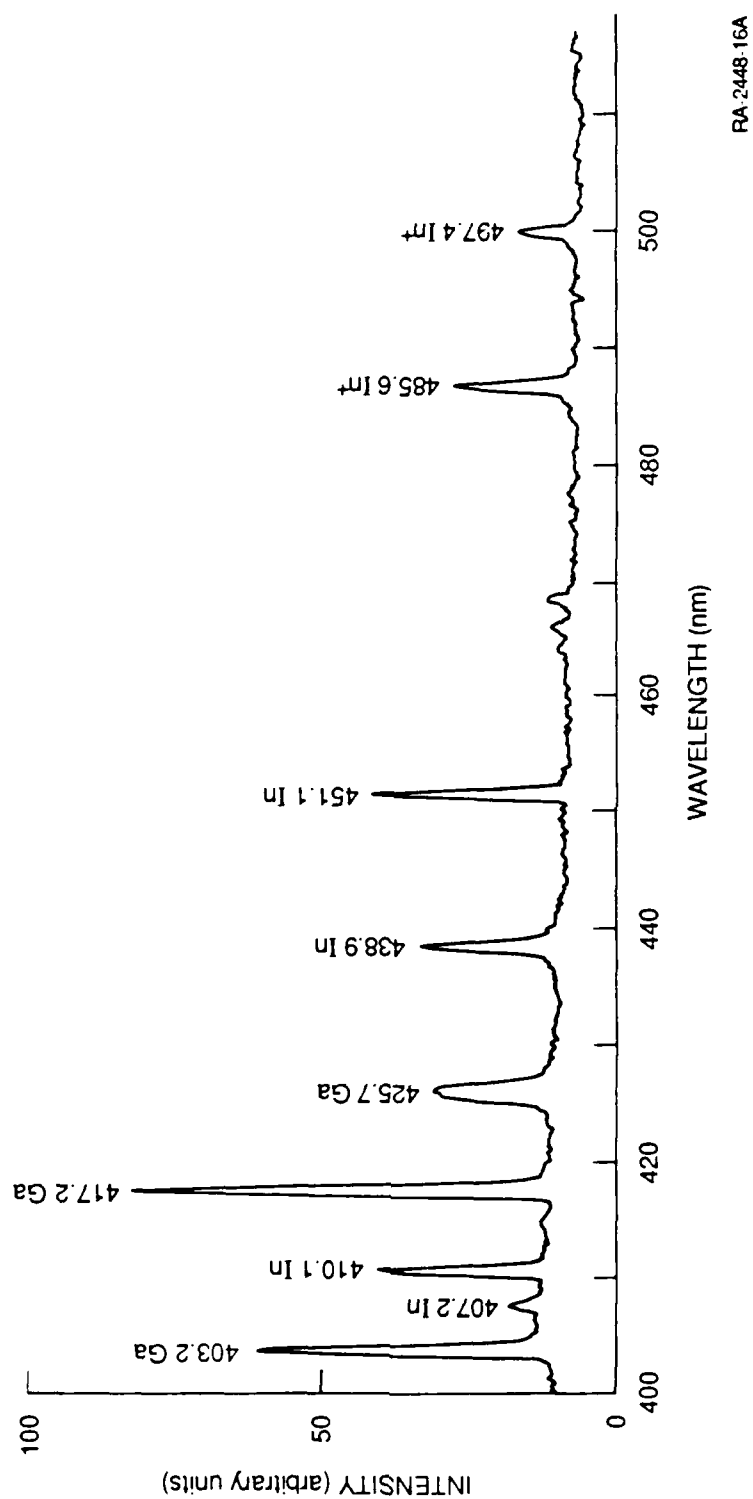


Figure 22. Optical emission spectrum of Ga/In emitter between 400 and 500 nm, with no added gas.

to those used to record the electron pulse signals in Figure 4. In this wavelength range, three lines are associated with neutral Ga and four lines arise from neutral In atomic emission. Two other lines can be associated with ionic indium transitions. Of particular interest is the line centered near 426 nm. This feature is clearly broader than the others and may be associated with a molecular species. Little is known concerning the optical emission spectra associated with Ga_2 , In_2 , and GaIn molecules. Ginter et al.⁸ have reported some electronic transitions arising from Ga_2 and In_2 ; however, most are at wavelengths in the UV range or longer than 500 nm. These authors also report a feature at 482.4 nm that they associate with the GaIn molecule. The prominent transition at 485.6 nm that appears in Figure 22 may be due to that species rather than to In^+ , although more detailed studies are required to establish this with certainty. In general, the lack of strong molecular emission and the presence of excited ions is indicative of very high effective temperatures in the emission region.

In contrast to the relatively simple spectrum of Figure 22, the optical emission spectrum associated with the enhanced Ga/In/Ar mode shown in Figure 23 is considerably more complex. The majority of transitions can be readily assigned to the argon atom. The wavelengths indicated in the figure are the known positions for a number of argon atomic lines.

Because the emitting species are confined to the region of the field emission tip, they are subjected to very high electric field strengths ($1 \text{ V}/^\circ$). Thus, the emission lines will be suitably Stark-shifted. Provided that the line positions can be determined with sufficient accuracy, it should be possible to use the measured shifts to determine the corresponding electric field strength at the point of emission. This method offers a simple diagnostic of the field-emission process. Unfortunately, the low resolution used to obtain the data in Figure 23 does not warrant a detailed analysis of this type. Nonetheless, the utility of this approach is apparent, and it will be exploited in the near future.

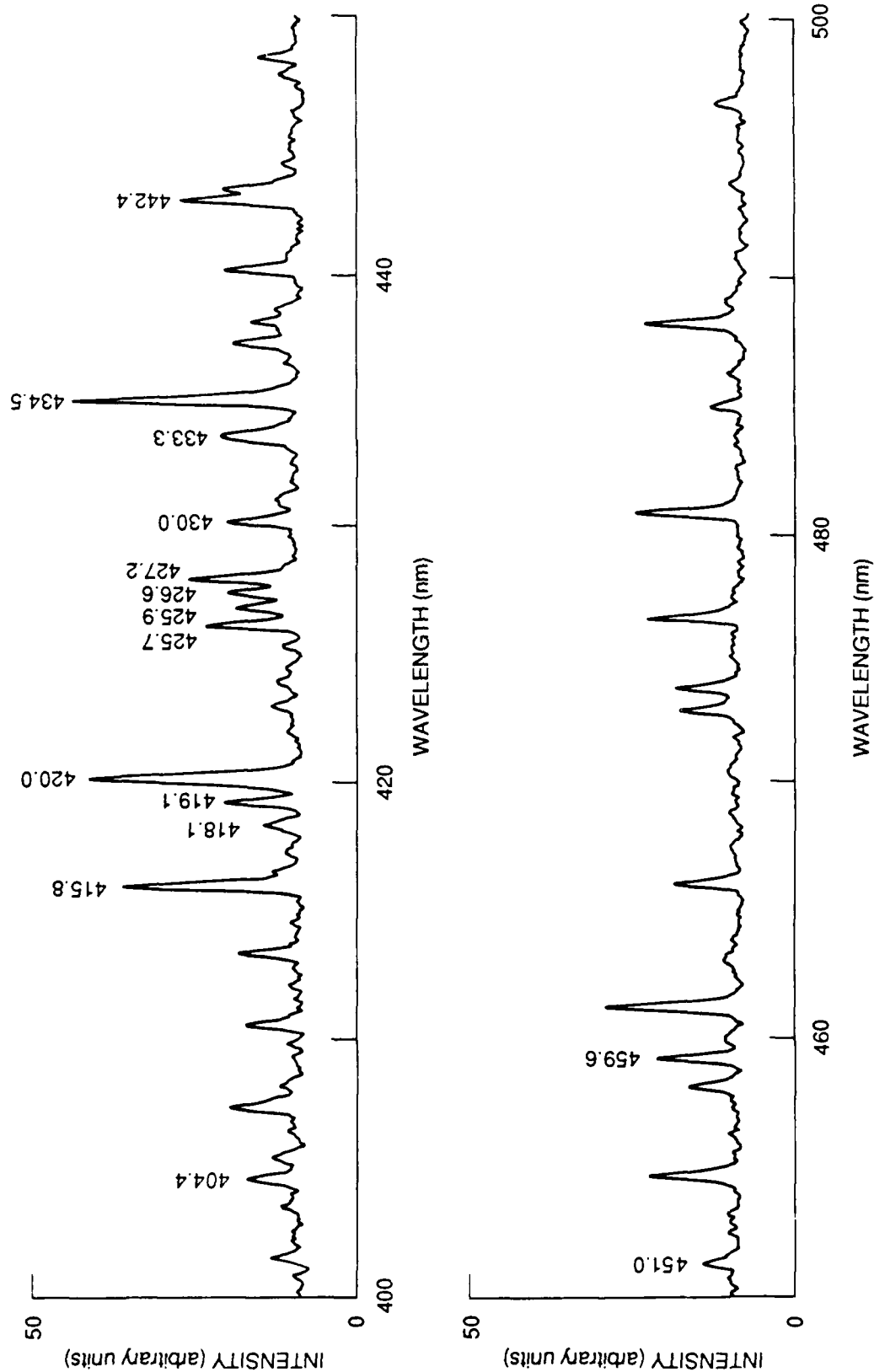


Figure 23. Optical emission spectrum of Ga/In emitter between 400 and 500 nm, with added argon gas. Wavelengths correspond to unshifted line positions (see text).

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CONCLUSIONS

Liquid metal field-emission sources appear to have desirable characteristics as the active element of a high-current repetitive switch. The results we obtained indicate that many of the operational parameters of these devices can be controlled, although the mechanisms are not yet understood. In particular, the enhanced mode of operation found for the Ga/In/Ar system gives very large, narrow current pulses by an unknown mechanism. The use of various diagnostics, including the dispersed optical emission, may provide some insight into these mechanisms.

Additional research is required to determine the optimum configuration for a practical switch. The choice of metals, the diode geometry, and the triggering mechanism will need to be addressed before the liquid metal field-emission device can be incorporated into an active switch.

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APPENDIX

CHARACTERISTICS OF A PULSED, LIQUID METAL FIELD-EMISSION SOURCE
FOR USE IN FAST HIGH-CURRENT SWITCHES

(To be published in Proceedings of SPIE Symposium on
Innovative Science and Technology, Volume 871, 1988)

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ABSTRACT

A liquid metal ion source (LMIS) of the type used for ion beam lithography can also be used to produce large pulses of electrons via field emission. These sources typically consist of a small capillary through which a liquid metal is forced. The application of a voltage between this capillary and an extraction anode causes the liquid metal to form a sharp cone. When the intense field at the tip exceeds the threshold for field emission, a large electron current flows from the tip to the anode. The production of this electron pulse results in the rapid heating of the liquid metal tip, leading to an explosive pressure increase and collapse of the tip. As the field is restored, the tip re-forms, with a resultant self-pulsing mode of operation. The pulse repetition rate, the average current, and the current per pulse are all functions of the metal composition, emitter geometry, and applied diode voltage. These characteristics are reported for a variety of conditions and show that a single emitter tip can produce current pulses in excess of 50 amperes, with a rise time of a few nanoseconds and a width of 5-50 ns. Repetition rates vary between 10 Hz and 20 kHz. In addition to the observed electron emission, optical radiation is also produced. The dispersed visible spectrum shows predominantly emission from neutral atomic species, presumably excited by electron impact in the gas phase.

INTRODUCTION

Many developing technologies, such as electromagnetic propulsion, directed energy applications, and controlled fusion, involve the use of pulsed power techniques. This technology normally incorporates capacitive storage of electrical energy that is rapidly delivered to a load by means of fast switches such as spark gaps. However, inductive storage is of considerable interest primarily because of the order of magnitude improvement in stored energy density. One key problem limiting the development of an inductive storage system is the lack of a fast, reliable, repetitive opening switch. A number of techniques are being investigated for the development of such switches, with the majority taking the form of electron-beam controlled discharge devices.^{1,2} The present study focuses on the application of a very different technology to the problem of fast repetitive switching: a vacuum triode with an active element formed by a liquid metal field-emission electron source. This novel electron emission source has the promise of providing low voltage control, fast response time, high electron emission current density, high voltage standoff, vacuum operation, and a long operational lifetime.

Positive ion sources based on field evaporation/field ionization of liquid metals have been under investigation for a number of years. These sources have been successfully operated in a dc mode to produce ions of a wide variety of elements, including atomic and molecular ions of Li, Cs, Sn, Ga, In, Hg, Au, Bi, Ge, and U. In general, the liquid metal ion source (LMIS) consists of a solid metal nozzle or needle, typically made of tungsten, that is wet with a continuous supply of a liquid metal. When an electric field is established between the emitter tip and a suitable extraction electrode, the liquid metal is drawn into a sharp point such that the electrostatic and

surface tension forces are balanced. The resulting cone tip is well described in the static case by the Taylor model;³ however, in the actual fluid dynamic operation of the source, the tip behavior may be more complex.⁴ Because of the very small radius of the cone tip (hundreds of Angstroms), the local electric field becomes sufficiently strong ($1 \text{ V}/^\circ$) to extract positive ions from the liquid metal. Total emission currents in excess of $100 \text{ } \mu\text{A}$ have been achieved in many cases, with very high long-term stability.

The conditions that exist at the tip of the LMIS described above can also produce electron field emission if the potentials are reversed. This type of source has been demonstrated by Swanson and Schwind.⁵ Although field-emission electron sources are well known and extensively used in electron microscopes, they have typically depended on solid, needle-point "whiskers" of tungsten to produce the requisite field strength. On the other hand, the use of liquid metal sources for intense electron field emission has not been investigated in a systematic manner.

When operated in the electron field-emission mode, a Ga/In liquid metal emitter produced extremely high peak currents in a free-running self-pulsing mode.⁵ Current pulses with peak values of 40-60 A have been measured from a single tip, with rise times of 2 ns and 3-5 ns full width at half maximum (fwhm). The pulse repetition rate depends on the RC time constant of the circuit and the power supply. Repetition rates of between 40 Hz and 80 kHz have been measured. In this mode, the current goes completely to zero after each pulse and stays at zero if the voltage is removed. The explanation offered for this pulsing behavior is that as the field is applied, electrostatic forces draw the liquid metal into a cone with decreasing tip radius. The tip radius at a given electric field strength depends primarily on the surface tension of the liquid metal. As the tip radius decreases, the local field strength in the

vicinity of the tip increases to the point where field emission of electrons becomes possible. Localized heating at the tip results from the energy-exchange processes that accompany field emission. This heating can be sufficiently rapid and extensive to evaporate the liquid metal in an explosive event that momentarily shorts the diode with a large burst of current. The tip then collapses because the field drops as the diode is shorted. However, as soon as the tip collapses and the current flow is interrupted, the field reappears, and the tip begins to re-form as the liquid metal flows into position to heal the damage. A new tip then begins to form, and the process repeats itself, leading to a rapid self-pulsing effect.

Two energy-exchange processes are responsible for the heating observed in a liquid-metal source described above. At low electron emission currents, the energy exchange is dominated by the so-called Nottingham effect. This effect, which can produce either heating or cooling of the cathode, arises from the net difference in energy between the source of electrons (the liquid metal) and the free electrons emitted by the tip. The second energy-exchange process is the more familiar resistive, or Joule, heating. This latter process becomes important at higher emission currents and is due to the finite electrical resistance of the metal. Since large numbers of free electrons must be supplied from the electrical source through the liquid metal to the tip, the Joule heating can produce a very rapid temperature rise. A single liquid metal field-emission tip operating in the self-pulsing mode would not yield a useful pulsed power system. However, the total peak current required for many practical switching applications could be achieved by an array of such liquid emitters. If a 10×10 array of sources were made so that each of the 100 sources produced about 50-A peak current pulses, then it would be possible to produce 5 kA of peak switched current. For such an array to work, all the

tips would have to "explode" very nearly simultaneously because of the shorting effect of the tip explosion. This would require accurate fabrication of the cathode structure, or individually controlled tips all acting in parallel, or both. One feature of the liquid emitter seems to be that the onset of the explosive emission is repeatable for a given tip. Thus, it may be possible to make a small array with tips that can be individually biased to within a few volts of the onset of emission and then pulsed together to trigger simultaneous emission. The maximum current pulse reported by Swanson and Schwind⁵ for a single tip was 250 A. Thus, a four-tip array with simultaneous triggering would switch a 1-kA pulse.

Another alternative would be to fabricate a much larger array such that enough tips would explode at any given time to switch the required current loads. In a 100 x 100 array, only 0.04% of the tips would have to trigger simultaneously to switch the same load. If the average emission pulse is 10 ns, and the self-pulsing rate is 100 Hz, then there is a high probability that four or more tips would trigger simultaneously. Thus, the multipoint array would not require individual tips to be controlled but rather would depend on the random pulsing of a large number of tips.

Another possible approach to the multitip array is the use of a linear source. Clampitt and coworkers⁶ have reported that when molten metal forms a thin film along a linear structure ("razor blade") in the presence of an strong electric field, a periodic cusp-like structure is generated. The periodicity of the cusps is determined by the field strength and the surface tension of the liquid. Each cusp then acts as a independent emission site, resulting in a one-dimensional, linear array of tips. Although Clampitt's

work demonstrated this type of source only for ion emission, it is reasonable to expect a similar effect to produce electron emission under the correct conditions.

The liquid metal field emitter has several appealing features for the fast, repetitive switch application. It can deliver very large peak currents in a pulsed mode without destroying itself. It is self-healing in the event of discharge, since the working tip material is resupplied by the liquid. The liquid-metal field emitter can supply its own positive ions for space charge neutralization. It can be shut off rapidly, and its emission is highly repeatable for a given geometry.

The nanosecond pulse lengths reported below and in the literature for liquid metal electron emission sources are too short with respect to the millisecond L/R time constants of many practical switching circuits. As noted above, liquid metal positive ion sources can easily operate in the dc mode. The explosive evaporation that has been observed for the Ga/In electron source does not occur in the ion emission mode, primarily because the Nottingham effect serves to cool the source rather than heat it. Thus, if the electron source can similarly be made to operate in a mode in which the Nottingham effect does not heat the liquid metal tips during emission, long-pulse or even dc operation should be possible.

The factors that govern both the magnitude and sign of the Nottingham effect are complex functions of the liquid material properties (surface tension, work function, heat capacity, thermal conductivity, etc.), the field strength, the fluid dynamics of the system, and emission characteristics of the tips. Thus, it is not possible to determine beforehand which systems would yield electron emission with little or no energy transfer to the liquid metal tip. For example, one attractive combination of emitter tip material

and substrate material is liquid cesium flowing on a molybdenum needle tip. A partial monolayer coverage of cesium on molybdenum is known to produce a surface of very low work function (1.1 eV). A number of other such combinations are known and may prove of value in this application. In fact, mixed emitter materials such as zirconium-oxygen-tungsten when used in a cold-cathode electron field-emission source have demonstrated significant cooling of the tips with increased emission.⁷

An additional possibility for controlling the emission characteristics of liquid metal tips is laser-assisted or -activated photoemission. Recent work on the electron emission characteristics of thin film alkali photocathodes indicates that large peak current density pulses (75 A/cm^2) can be readily obtained using low power laser excitation.⁸ This behavior suggests that the liquid metal tips could similarly yield large current density pulses of electrons under laser irradiation. This approach has the advantage of a very rapid switching time, governed by the laser pulse shape. Thus, an array of liquid emitters (either two-dimensional or linear cusps) could be biased to a point just below their nominal field-emission point and then switched on by a low-power, nanosecond laser pulse. If the tip bias voltage were simultaneously raised above the emission threshold value, then the electron emission initiated by the laser pulse might be sustained by the static field. This combination could produce long-pulse or even dc switch action with very fast switching time and high peak current density.

EXPERIMENTAL DETAILS

The vacuum test stand used for this work consists of a large (45-cm diameter, 25-L volume) aluminum chamber pumped by a baffled 6-in. oil diffusion pump. Base pressures are typically 1×10^{-6} Torr, rising to varying degrees (see below) when the source is operating. The front flange of the chamber is fabricated from Lucite to allow continuous observation of the emitter tips under actual operating conditions. In addition, a smaller quartz window is provided on the rear vacuum flange to permit observation of the optical emission spectrum that accompanies the electron emission. As shown schematically in Figure 1, the emitter tip forms the cathode of a simple diode structure. The anode is formed by an extraction aperture and collector plate that are spaced apart by 10 cm but electrically connected. The tip is mounted such that it is coplanar with the 0.25-in. diameter extraction aperture. Electrically, the anode structure is connected to a variable 0- to 25-kV power supply through a ballast resistor. The cathode tip is grounded through the 500 input impedance of a Tektronix model 2430 digital storage oscilloscope. The ballast resistor used was either 10 M Ω or 100 M Ω , and the overall capacitance of the system was approximately 30 pF.

In these preliminary experiments, we have investigated a number of liquid-metal emitter tip configurations, including a commercially available tungsten needle.⁹ This needle has an nominal opening of 0.001 in., as shown in Figure 2(a). In the simplest configuration, this needle is mounted to a Swagelock fitting connected to a length of 0.25-in. diameter Teflon tubing. The tubing exits through the vacuum chamber and serves as the feed source for the liquid metal and permits adjustment of the pressure behind the emitter tip. The Teflon feed line can be evacuated or pressurized with an added gas. This arrangement

was used only for metals that are liquid at room temperature. Two other methods were used, both involving an open pool of liquid metal. The configuration shown in Figure 2(b) consisted of an etched tungsten whisker that protruded through a small droplet of liquid metal held in a depression formed in the cathode plate. The third arrangement, shown in Figure 2(c), was similar but lacked the whisker and was equipped with a ceramic heater element below the liquid metal pool, so that higher melting point materials could be studied.

Operation of the liquid metal field-emission source is straightforward. Before the test stand is evacuated a supply of metal is placed in the Teflon tube near the emitter tip for configuration 2(a), or in the appropriate locations for configurations 2(b) and 2(c). During pumpdown of the test stand with tip 2(a), the volume behind the liquid metal supply is evacuated using the pumping system shown in Figure 1. This step is prevents the trapped gas behind the liquid metal from forcing the alloy through the tip into the low pressure region of the main chamber. Once the test stand has been evacuated, the liquid metal must be pressurized, so that it begins to flow through, and wet, the tip. Once liquid metal is seen to protrude from the tip, the high-voltage bias can be applied. For configuration 2b, no additional preparations are needed, since the liquid metal readily wets the tungsten whisker and flows along its length to the tip. Configuration 2c was typically used with metals requiring heating, such as indium and potassium. A thermocouple attached to the cathode allowed the metal temperature to be adjusted as needed.

Depending on the exact tip configuration, prior conditioning, etc., the voltage threshold for electron emission may vary from a few to 15 kV. At threshold, the electron emission is somewhat erratic, triggering the scope at random. However, with only a modest increase in voltage above threshold (1-200 volts), the emission becomes more stable. By means of the averaging

capability of the 2430 oscilloscope, it is possible to accumulate a number of electron pulses so that an accurate measure of the average pulse height and time behavior can be made.

EXPERIMENTAL RESULTS

Pulsed Electron Emission Characteristics

Figure 3 shows a typical trace recorded in the manner described above using tip configuration 2(a) with Ga/In (75:25). The average peak pulsed electron current is seen to be 26 amperes. The pulse rise time is measured to be 1.6 ns, with an fwhm of 3.5 ns. Under our experimental conditions (effective circuit capacitance of 30 pF), the measured repetition rate was 10-20 kHz. Although this pulsing rate is somewhat slower than that reported by Swanson and Schwind⁵ (40-80 kHz), the pulse shape and peak current are comparable. This simple emitter configuration yielded stable operation for many hours with a signal of the type characterized by the trace in Figure 3. It was necessary to apply a slight positive gas pressure behind the liquid metal however, in order to sustain this long-term operation. Even under these conditions, the pressure rise in the chamber amounted to only 5×10^{-5} Torr. This small pressure rise indicates that the gas used to force the Ga/In alloy through the tip does not pass directly into the vacuum chamber.

An alternative operational mode was observed when the added gas pressure was increased beyond that required to sustain a normal liquid metal tip. This alternative mode was characterized by a greater rise in chamber pressure ($5-8 \times 10^{-4}$ Torr), indicating that the added gas was "channeling" through the liquid metal and passing directly into the vacuum chamber. A typical electron pulse in this mode is shown in Figure 4 using argon gas with the same Ga/In alloy that produced the results in Figure 3. The peak electron current clearly is greatly enhanced, reaching 78 A. In addition, the rise time is now less than 1 ns, while the fwhm is also reduced to 1.4 ns.

The mechanism responsible for this improved performance is not yet understood. However, prolonged operation in this mode (many hours) resulted in a significant erosion of the emitter tip. This erosion typically resulted in an increase in throat size from 0.001 in. to as much as 0.010 in. Some additional qualitative observations can be made concerning operation in the enhanced mode relative to the normal mode. In the normal mode, electron emission is accompanied by optical radiation produced at the tip. This optical emission was also observed by Swanson and Schwind to be localized at the tip [cf. Figure 4(c) in reference 5]. Visually, this emission appeared to be bluish-white, with a very small spatial extent. On the other hand, in the added gas mode with argon, the appearance of the optical emission changed significantly. Under this mode, the spatial extent of the emission was much larger (many millimeters) and had an appearance more characteristic of an argon emission spectrum. These qualitative observations have been substantiated by measurements of the dispersed emission spectra (see below). In addition to the changes in the light emitted from the tip region under the two operating modes, the added gas mode also produced an incandescent region just at the rim of the emitter. Because of the small size of the tip, this region cannot be localized to the inside of the tip, the rim itself, or the entire tip region. The incandescence seems to indicate that the tip region is being bombarded, most likely by positive ions accelerated in the extraction field. In addition to causing the incandescent glow, these ions may also generate secondary electrons that would contribute to the enhanced field-emission pulse. This mechanism does not, however, address the changes in the temporal behavior of the electron emission. In fact, a simple calculation shows that for the experimental extraction field strength of 3.2×10^4 V/cm (10 kV between the tip and the extraction electrode, 0.32-cm spacing), argon ions could

only reach the tip in a time short compared with the 1 ns rise time of Figure 4 if they were formed within 4×10^{-4} cm of the tip region. However, ions formed that close to the tip would only be accelerated to 12 eV before striking the emitter. This energy is not sufficient to produce secondary electrons. Moreover, the primary electrons emitted by the tip would similarly have only about 12 eV of energy at the 4×10^{-4} cm distance, where argon ions would need to be formed by electron impact ionization. Since this energy is below the argon ionization potential, this mechanism does not seem to fit the observations. Nonetheless, some interaction between the added gas and the tip causes the incandescence, although it is not clear at this time whether this process is related to the enhanced electron emission or altered pulse shape.

Several brief experiments were conducted using added gases other than argon. Both helium and hydrogen produced similar results: enhanced electron emission with a corresponding narrowing of the pulse length. Because the exact conditions are difficult to reproduce using the existing configuration, it is not possible to determine if the gas pressure and liquid metal supply were comparable from one gas species to the next. Thus, it is not possible from these results to determine if one of these gases is more effective than another at enhancing the electron emission. This type of quantitative comparison requires a configuration that uses an independent liquid metal feed system so that the emitting tip can be maintained constant while only the added gas species is changed.

An alternative method of adding argon gas to the system was also tested. Rather than adding the gas to the liquid metal feed system, the gas was simply admitted to the vacuum chamber to give the same approximate pressure rise. The enhanced mode of operation could not be produced under those conditions, but rather the emitter behaved exactly as with only the Ga/In. Thus, it

appears important for the argon to be at a relatively high pressure at the local site of electron emission.

Two major shortcomings of the simple needle-type emitter tips are the difficulty sometimes encountered in wetting the tip and producing a continuous flow of metal and the erosion noted in enhanced mode operation. By way of an attempt to overcome these problems, the alternative field emission device shown schematically in Figure 2(b) was tested. For these tests, a ternary eutectic of Ga/In/Sn (62.5/21.5/16) was used having a melting point of 10.7°C . This configuration operated reliably, producing modest peak currents in the range from 5 to 10 A. The measured rise time was generally long, 30-50 ns, with an fwhm of 50-75 ns. This type of field-emission source has the advantage of simplicity over the needle-type source, at the expense of lower currents. A possible reason for the reduced peak current levels is the limited supply of metal available at the tip of the tungsten whisker. Configuration 2(c) does not have this limitation, although the lack of a cathode whisker can result in electron emission from varying points on the surface of the liquid metal.

Figure 5 shows the measured electron emission peak shape as a function of the power supply voltage for liquid indium using emitter type 2(c). Several observations can be made from this data. First, the pulse widths are larger than for emitter type 2(a), although comparable to those for type 2(b). The emission pulse for a 10-kV applied potential (near threshold for emission) shows a slower rise time and a peak current of 5 A. Increasing the voltage to 15 kV decreases the rise time and increases the peak current to 7 A. A further increase in the voltage to 20 kV produces no substantial change in either the temporal behavior or the emitted peak current.

As noted above, the electron emission characteristics of these devices depend on a number of factors, including the physical properties of the metals themselves. The electric field in the vicinity of the emitter tip is determined by the radius of curvature of the liquid metal, which in turn is proportional to the one-half power of the surface tension (γ_s). Thus, the threshold voltage for field emission in a fixed geometry diode should show this dependence on surface tension. Figure 6 presents field-emission measurements made using indium ($\gamma_s = 560$ dyn/cm), gallium/indium (75:25, $\gamma_s = 690$), and potassium ($\gamma_s = 86$). These plots give the diode current (as determined by the power supply drain) as a function of the applied voltage using a 10-M Ω ballast resistor [Figure 6(a)], and a 100-M Ω ballast resistor [Figure 6(b)]. It is apparent from these data that the threshold for field emission is very similar for the Ga/In and In liquid metals and considerably lower for the K case. This trend is qualitatively in keeping with the above cited dependence on surface tension.

In each case, the average current is a linear function of the voltage over the range measured, and furthermore the results with the 100-M Ω ballast resistor are, to a reasonable approximation, just a factor of 10 smaller than the corresponding 10-M Ω results. This linearity and scaling with load resistor indicate that the current/voltage limit is set by the ability of the power supply to charge the circuit to the required voltage after the previous current pulse. Thus, the RC time constant of the system should determine the repetition rate of the diode provided that the total power required is within the limits of the power supply. Figure 7(a) shows the measured repetition rate for an indium liquid-metal electron emitter of the type 2(c) configuration. As expected, the pulsing rate is found to be linear with the applied voltage. Interestingly, since both the average power supply drain current and

the pulsing rate are linear functions of the applied voltage, the current delivered per pulse must be constant. This behavior is also demonstrated by the results shown in Figure 7(a). Apparently, once the threshold is exceeded, the electron pulse size cannot be measurably increased by increasing the diode voltage. This implies that the maximum possible emitting area (the tip of the Taylor cone) is active for voltages just above threshold. The only effect of increasing the voltage is to decrease the time required for the field to become reestablished after each pulse.

Similar results are found for emitters using both Ga/In and the Ga/In/Sn alloy. In each case, the current per pulse is in the range from 0.3 to 0.35 μA . In contrast, the corresponding results for the potassium emitter are shown in Figure 7(b). Here, the pulse rate is much higher than for any of the other materials studied; however, the current per pulse is considerably lower, 0.052 μA . The origin of this reduced emission current per pulse is not clear, although it may be associated with the differing work functions and thermal conductivities of these metals.

Optical Emission Studies

Under normal operating conditions, the liquid metal field emission electron source produces a considerable level of optical radiation. As noted above, the spatial extent and qualitative appearance of the optical emission changes with the mode. With only the Ga/In, the emission appears at the very tip of the needle and is bluish-white. This emission was also observed and photographed by Swanson and Schwind.⁵ In the enhanced mode with argon as the added gas, the optical emission is more diffuse, extending many millimeters from the tip, and has an appearance more characteristic of argon discharge. Although this optical emission was observed previously, the dispersed spectrum

was not measured. With the other metals, a similar visible emission was observed in each case to be localized at the electron emission site.

A simple experimental arrangement was used to record the optical emission spectrum produced by the liquid metal field-emission source. The light from the emitter tip was focused onto the entrance slit of a scanning 0.5-m monochromator equipped with an RCA 8850 photomultiplier tube. A PDP 11/2 computer scanned the monochromator while simultaneously counting the photon pulses. The overall light collection efficiency was not high, and wide monochromator slits were generally needed to obtain measurable signal levels. The resulting spectral resolution was typically 0.5-1 nm. This resolution is sufficient to identify many of the observed emission lines, particularly those associated with the liquid metals and argon; however, it is too low to assist with the identification of a number of the unassigned lines (see below). Furthermore, because of the low signal levels, long scan times were required (20-60 minutes), during which it was difficult to maintain the steady operation of the source. Thus, relative peak heights cannot provide reliable information. Optical emission spectra were recorded using both emitter types 2(a) and 2(c), the latter provided greater signal levels.

Figure 8 demonstrates that the light production process is directly associated with the electron pulse. The lower trace shows the typical electron pulse for an indium emitter of type 2(c) at 10 kV applied voltage. The upper trace shows a photon pulse measured directly at the anode of the multiplier tube. The observed 50-ns delay can be accounted for by the photoelectron transit time of the 8850 phototube.

Figure 9 shows a typical optical emission spectrum between 400 and 500 nm for a Ga/In liquid-metal emitter. The conditions were similar to those used to record the electron pulse signals in Figure 3. In this wavelength range,

three lines are associated with neutral Ga and four lines arise from neutral In atomic emission. Two other emission lines can be tentatively assigned to transitions associated with In^+ . Little is known concerning the optical emission spectra associated with Ga_2 , In_2 , and GaIn molecules. Ginter et al.¹⁰ have reported some electronic transitions arising from Ga_2 and In_2 ; however, most are at wavelengths in the UV range or longer than 500 nm. Preliminary spectral studies in these regions did not reveal any significant emission lines attributable to molecular species. Ginter et al.¹⁰ also report a feature at 482.4 nm that they associate with the GaIn molecule. The prominent transition at 485.6 nm seen in Figure 9 may be due to that species rather than to In^+ . In general, the lack of molecular emission features and the presence of excited ions is indicative of very high effective temperatures in the region near the field-emission site.

In contrast to the relatively simple spectrum of Figure 9, the optical emission spectrum associated with the enhanced Ga/In/Ar mode shown in Figure 10 is considerably more complex. The majority of transitions can be readily assigned to the argon atom. The wavelengths indicated in the figure are the known positions for a number of argon atomic lines. It appears that the Ga and In transitions observed in Figure 10 are not as intense as those arising from the argon.

Because the emitting species are confined to the region of the field emission tip, they are subjected to very high electric field strengths ($>1 \text{ V/\AA}$). Thus, the emission lines will be suitably Stark-shifted and broadened. Provided that the line positions can be determined with sufficient accuracy, it should be possible to use the measured shifts to determine the corresponding electric field strength at the point of emission. Similar techniques have been used to diagnose a rare gas discharge,¹¹ and this method

may offer a simple diagnostic of the field-emission process. Unfortunately, the low resolution used to obtain the data in Figures 9 and 10 does not warrant a detailed analysis of this type.

Triggered Operation

Because the threshold for electron field-emission is stable for a given emitter configuration and liquid metal, it should be possible to trigger the electron pulse. The simplest approach is to hold the diode potential just below threshold for emission and then rapidly raise the diode voltage in excess of the field-emission threshold. With emitter type 2(c) operating with potassium, some preliminary triggering tests were made. A high-voltage pulse generator was capacitively coupled to the anode, providing a variable voltage pulse (0.5-2 kV) of 1- to 40- μ s duration. The diode was biased to within 200 volts of threshold and the pulse generator triggered. Although the liquid-metal emitter did trigger, its operation was not as reliable as expected. It was not possible to find a set of conditions (dc bias, pulse voltage, pulse length, etc.) that would give reliable triggering. Moreover, when the diode did trigger, there was a considerable uncertainty in the time of electron emission relative to the trigger pulse. In general, for trigger pulses of 10- to 40- μ s duration, the electron pulse would occur with a seemingly random delay of the same order of magnitude, 10-40 μ sec. One possible difficulty is the fact that the trigger pulse must be coupled into the anode circuit outside the vacuum system. The anode circuit may present a large inductive load, so that the pulse is degraded considerably at the anode itself.

CONCLUSIONS

Liquid-metal field-emission electron sources appear to have desirable characteristics as the active element of a high-current repetitive switch. These preliminary studies have shown that many operational parameters of these devices can be controlled, although the mechanistic details are not yet understood. In particular, the enhanced mode of operation found for the Ga/In/Ar configuration gives very large, narrow current pulses by an unknown mechanism. The use of various diagnostics, including measurements of the optical emission spectra, may provide insight. Additional research is required to ascertain the optimum system for a practical switch, with the choices of liquid metal, emitter configuration and material, and triggering method of primary importance. The difficulties encountered with the simple triggering experiments must be understood before any practical application of this technique can be considered.

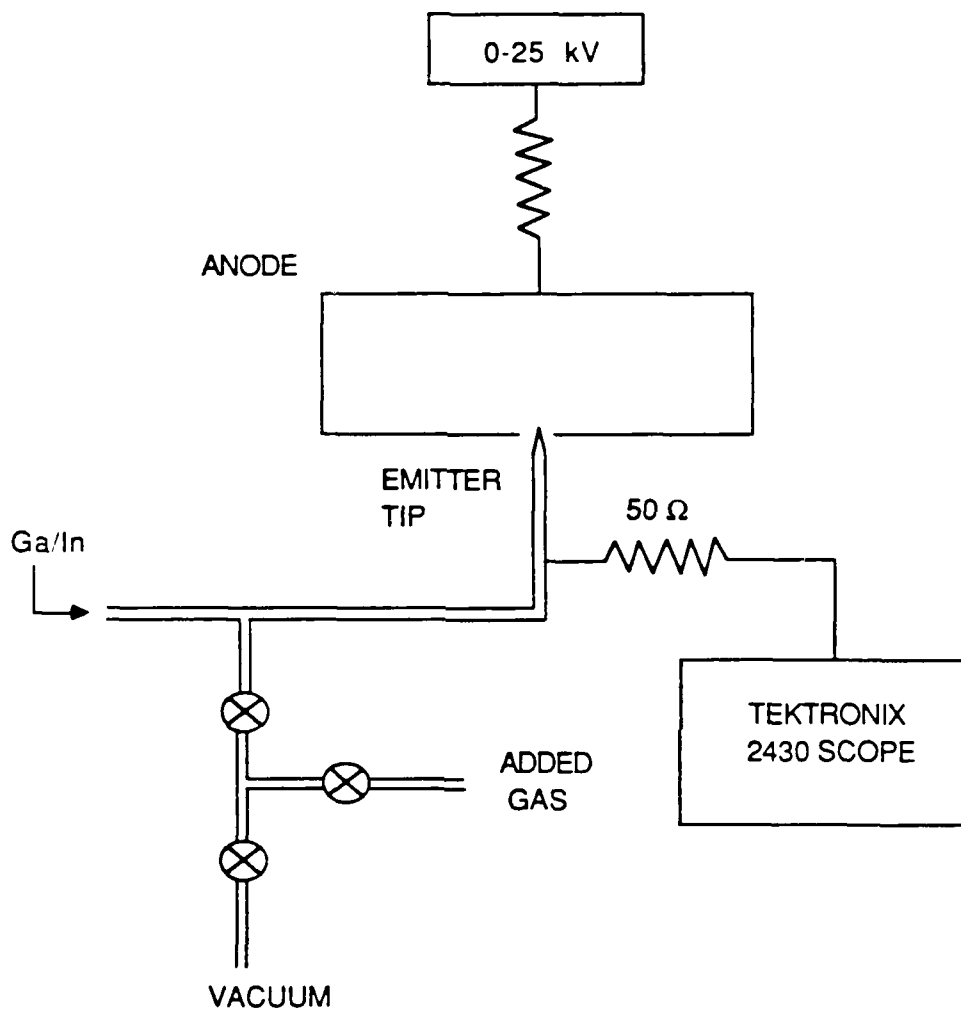
ACKNOWLEDGEMENTS

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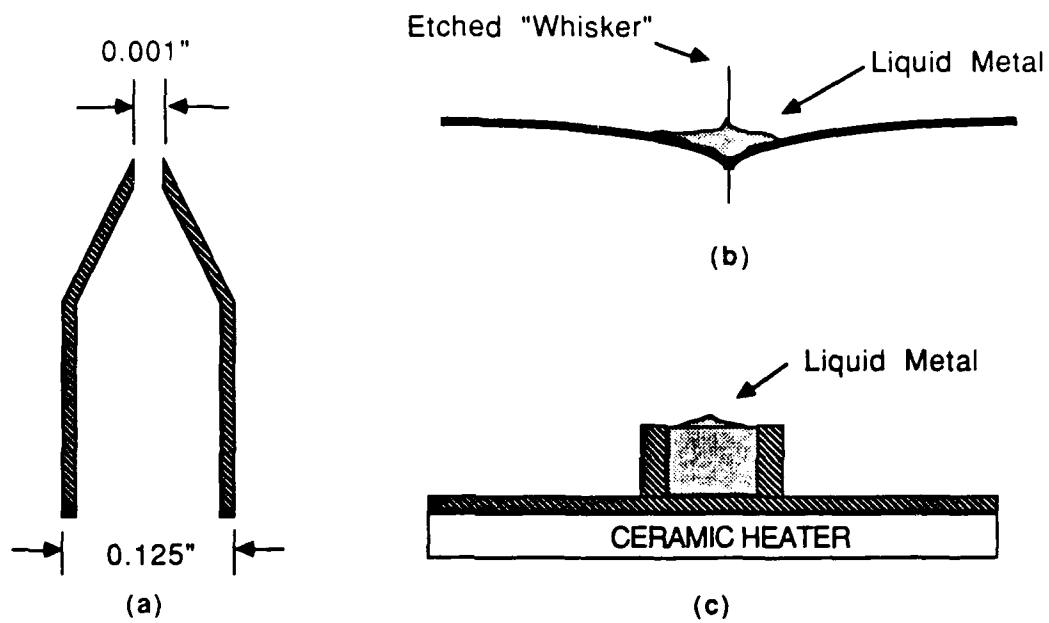
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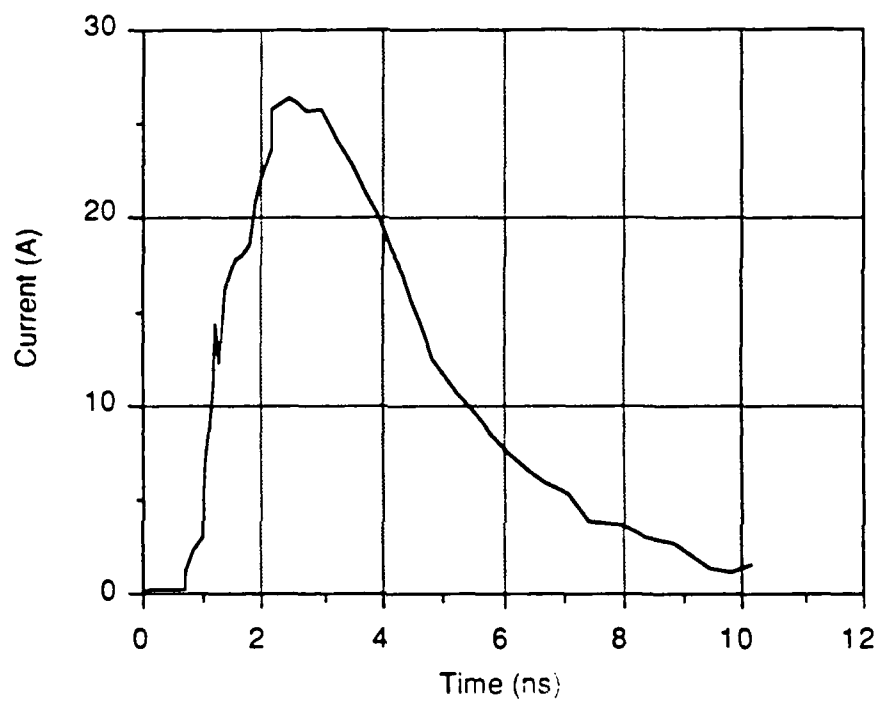
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Figure 1. Experimental configuration used to measure pulsed electron field-emission characteristics.



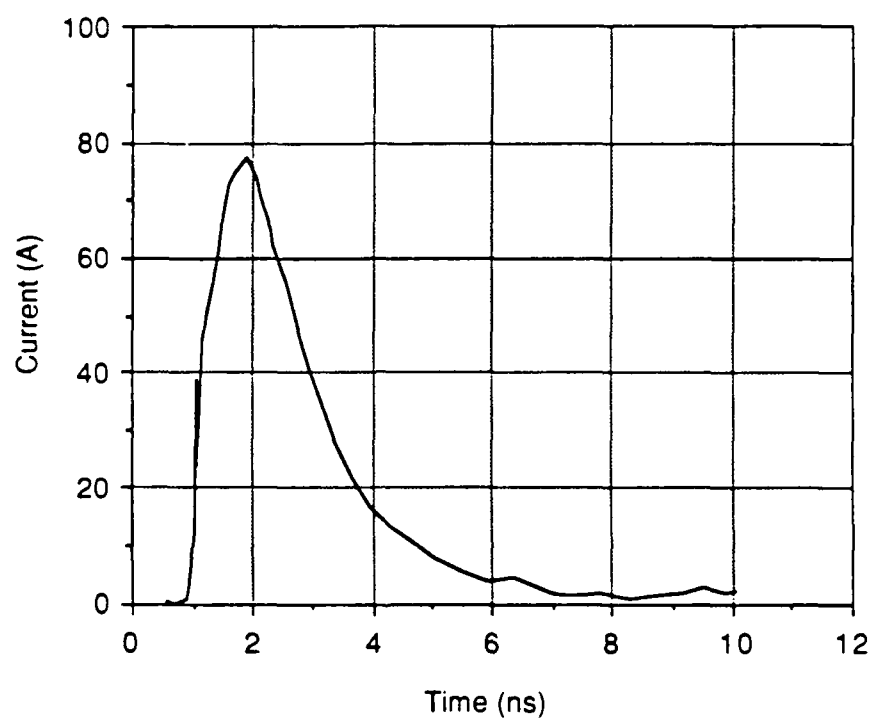
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Figure 2. Emitter configurations: (a) tungsten nozzle; (b) liquid pool with tungsten whisker; (c) heated liquid pool.



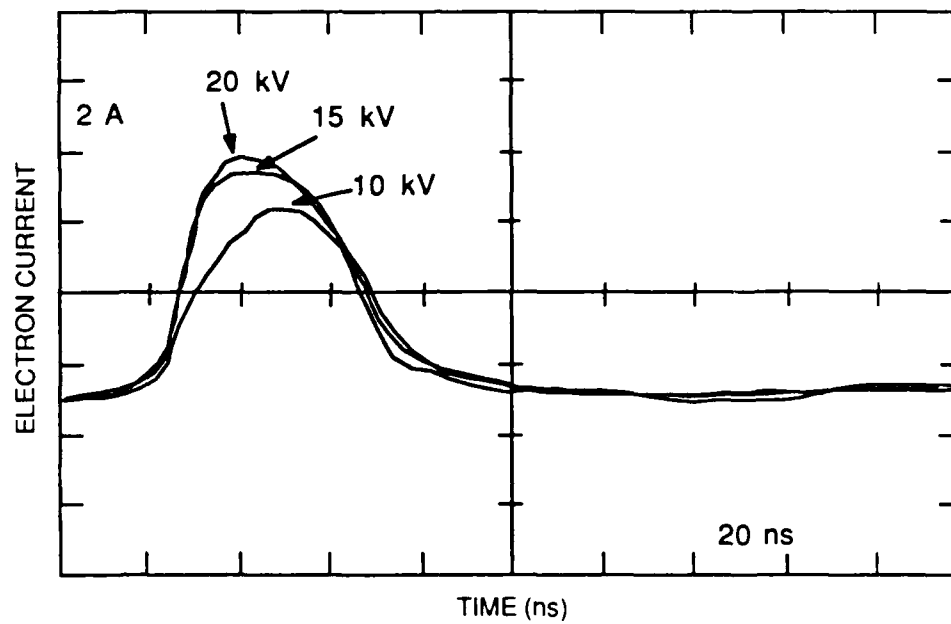
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Figure 3. Field-emission electron pulse for Ga/In (75/25) with anode at 10 kV.



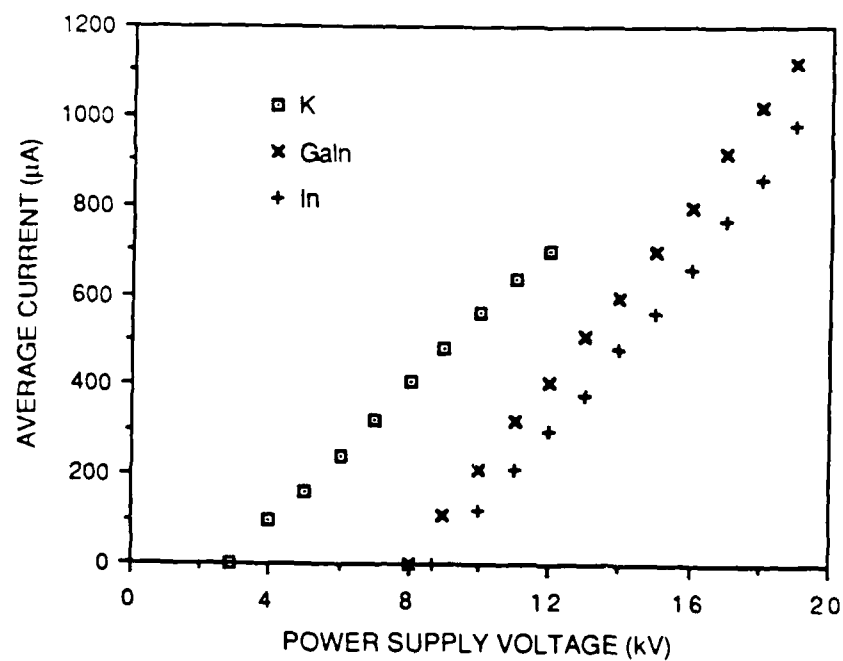
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Figure 4. Field-emission electron pulse for Ga/In (75/25) with added argon gas at 10 kV anode voltage.

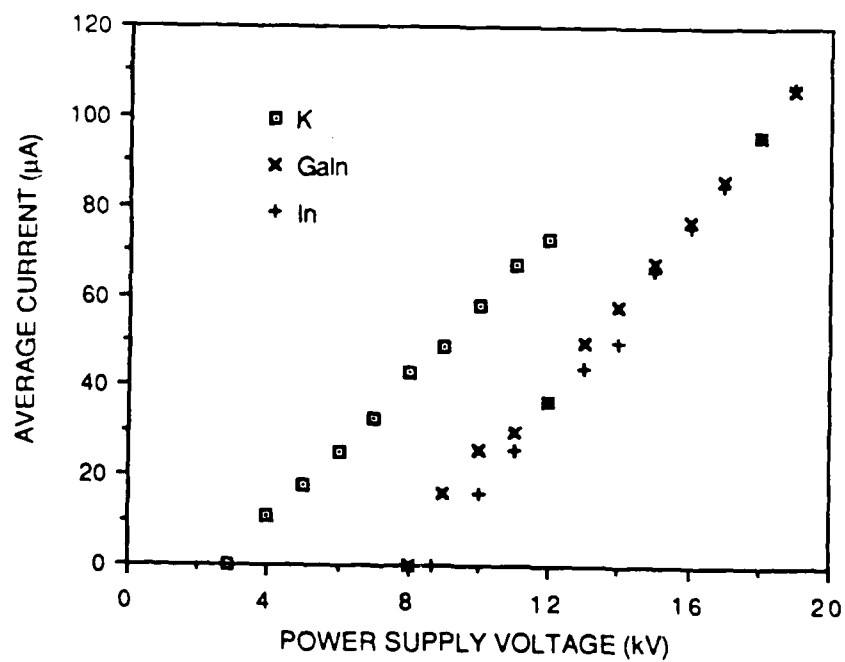


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Figure 5. Electron emission pulse shape variation with power supply voltage for a fixed cathode-anode spacing.
Emitter material is indium.



(a)

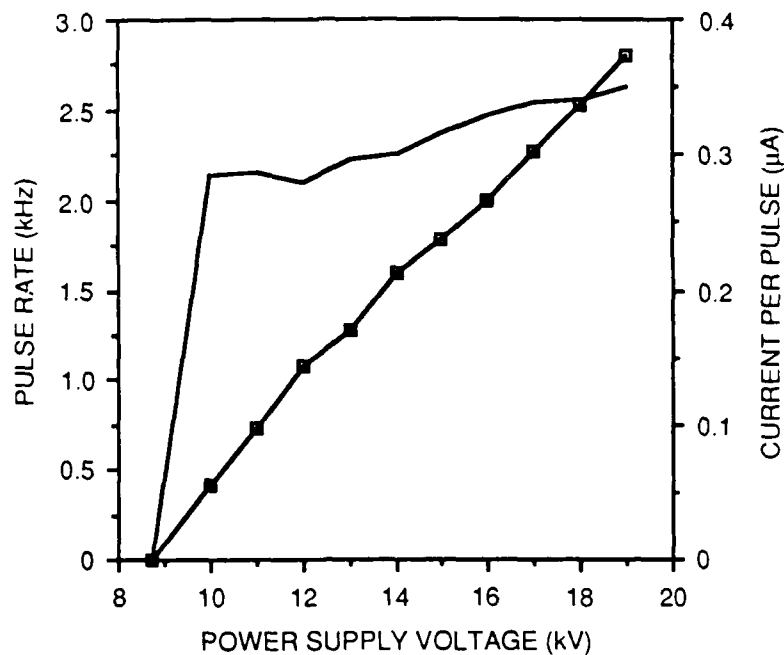


(b)

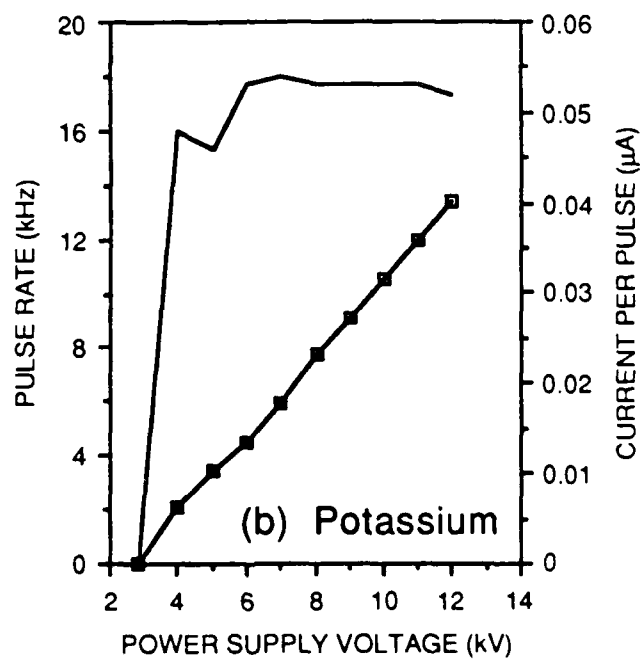
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Figure 6. Average electron emission current as a function of the power supply voltage.

Ballast resistor: (a) 10 MΩ; (b) 100 MΩ.



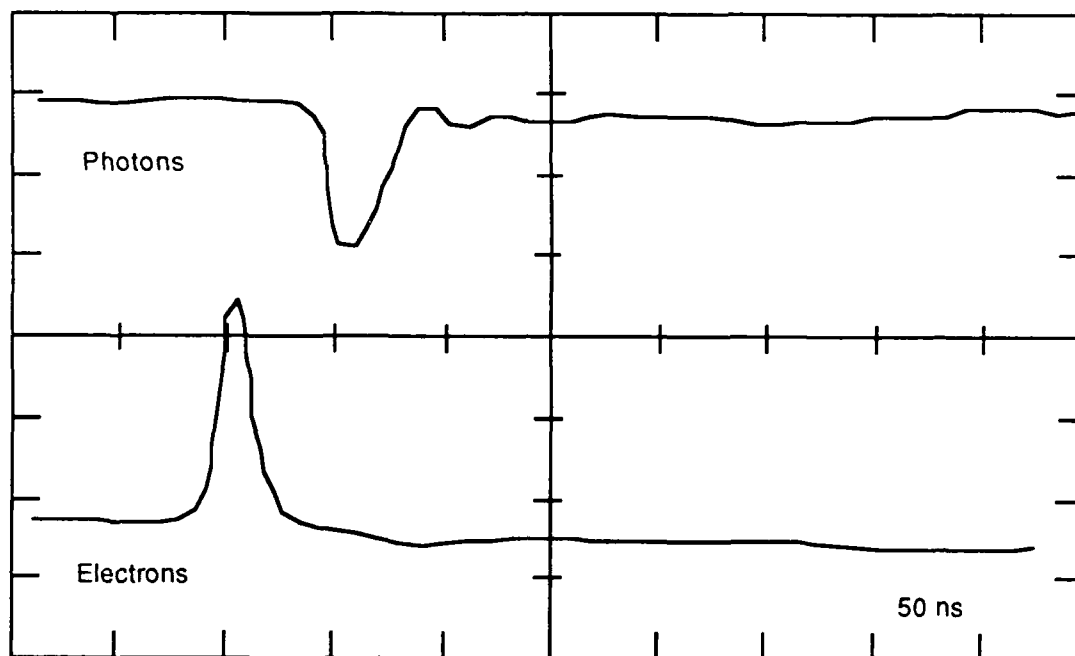
(a) Indium



(b) Potassium

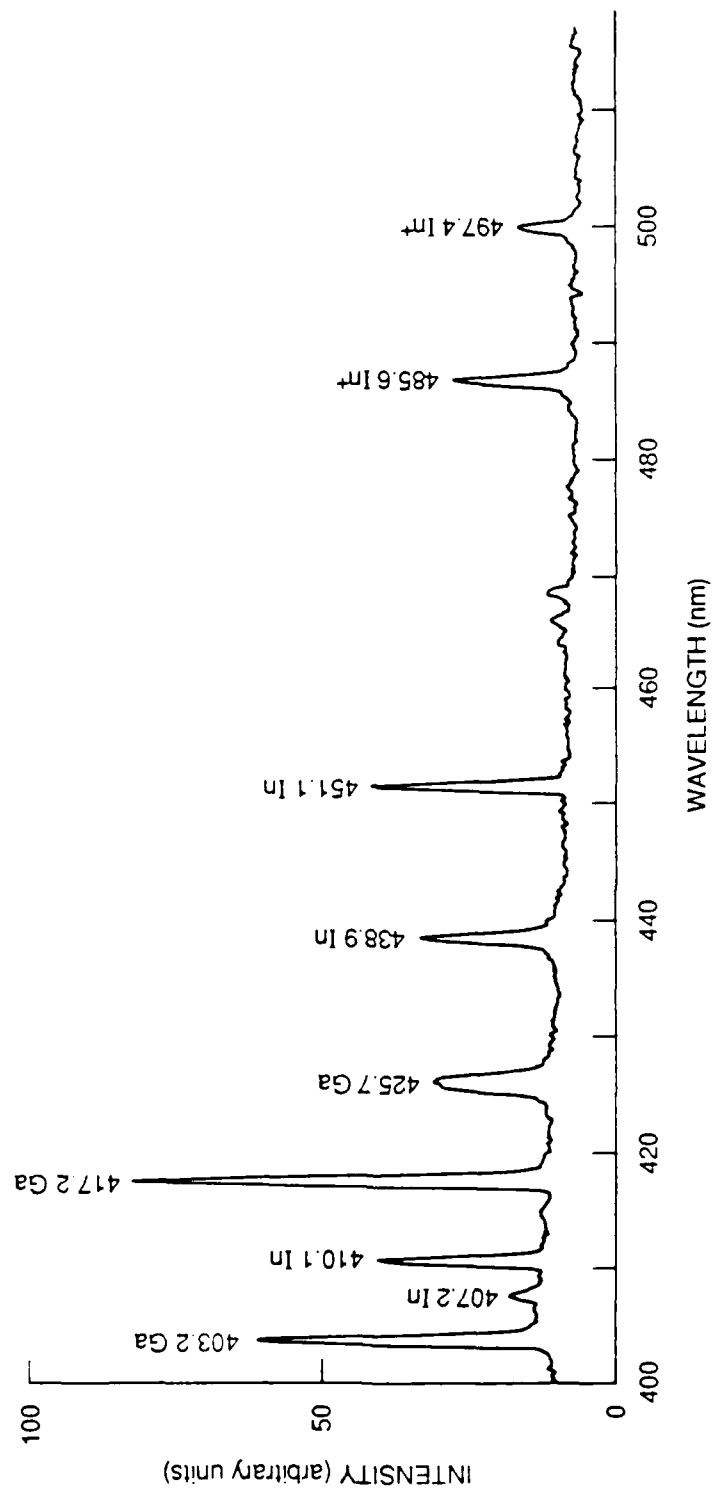
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Figure 7. Pulse rate (\square) and current per pulse for: (a) indium and (b) potassium liquid metal field electron emitter as a function of the applied diode voltage.



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Figure 8. Electron and photon emission signals for an indium emitter at an applied diode voltage of 10 kV.



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Figure 9. Optical emission spectrum of Ga/In emitter between 400 and 500 nm, with no added gas.

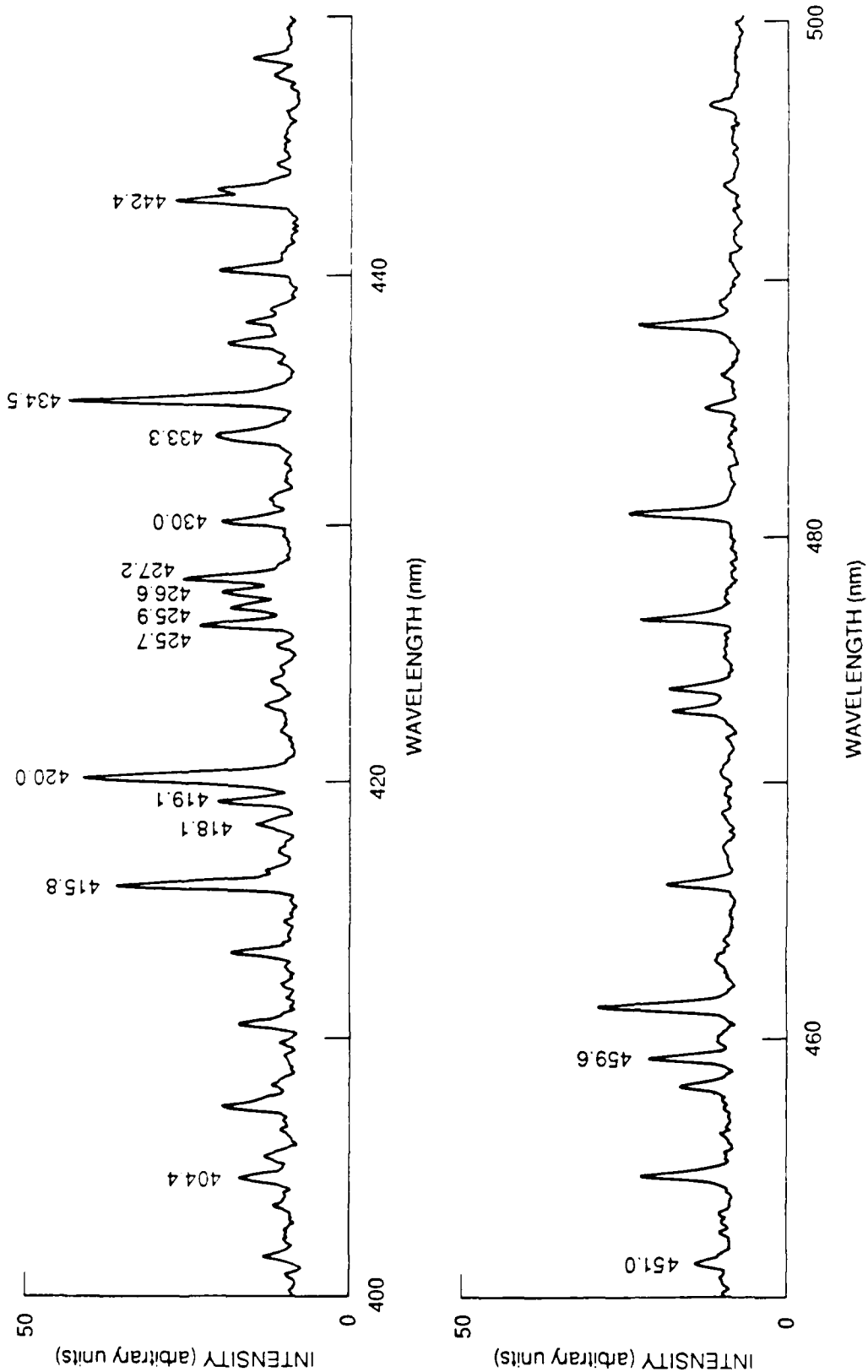


Figure 10. Optical emission spectrum of Ga/In emitter between 400 and 500 nm, with added argon gas. Wavelengths correspond to unshifted line positions (see text).

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